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AIRCRAFT ATTITUDE AWARENESS WORKSHOP PROCEEDINGS

Col. Grant B. McNaughton, editor

Control & Display Branch (WRDC/FIGR)
Cockpit Integration Directorate
Flight Dynamics Laboratory
Wright Research and Development Center, Air Force Systems Command
Wright-Patterson AFB, OH 45433-6553

Life Support SPO
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson AFB, OH 45433

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AIRCRAFT ATTITUDE AWARENESS WORKSHOP

FLIGHT DYNAMICS LABORATORY
BLDG. 146, RM. 203
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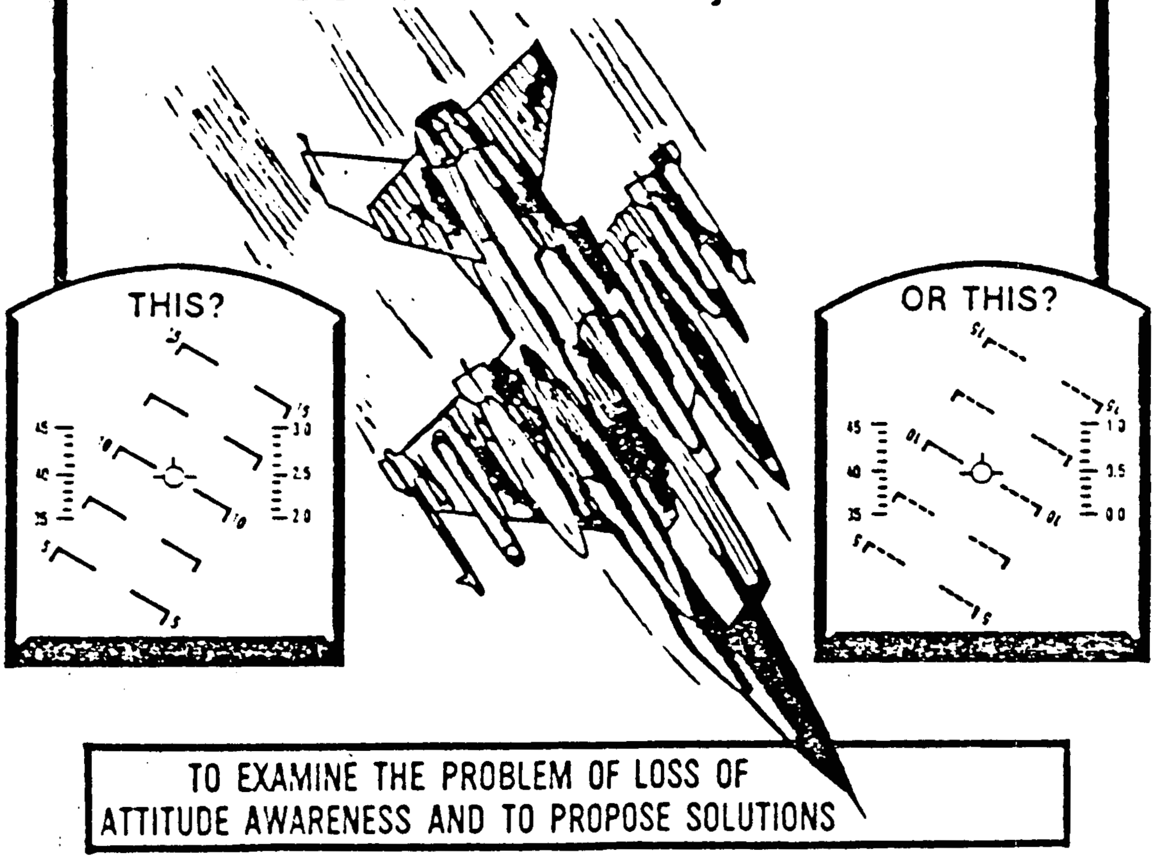

TO EXAMINE THE PROBLEM OF LOSS OF
ATTITUDE AWARENESS AND TO PROPOSE SOLUTIONS

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14 ABSTRACT

This report constitutes the proceedings of a workshop on Aircraft Attitude Awareness held at WPAFB, OH. 8-10 Oct 1985. The purpose of the workshop was to address the problem of loss of aircraft attitude awareness, primarily in the single-seat fighter attack aircraft, to recommend practical fixes to current operational aircraft and training measures to overcome their deficiencies, and to recommend initiatives to ensure that problems in the pilot-vehicle-interface of present aircraft be considered in the design of future aircraft, e.g., ATF.

There were a number of findings and recommendations to prevent collisions with the surface, to improve displays for orientation and other critical control parameters, to improve aircraft for the enhanced night-weather role, to improve training, and to improve communications.

15. SUBJECT TERMS
Ground collision avoidance system; Primary dedicated attitude display; Head-up display improvements for attitude; Enhanced night/weather role; Training use of HUD and use of vision; Automatic recovery systems; Virtual helmet mounted display technology; G-limiter by-pass; Non focal visual mode sensory cues; Three-dimensional sound; Standby attitude indicator; Noise canceling headset; Callout of selected parameters on request.

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AIRCRAFT ATTITUDE AWARENESS WORKSHOP
BUILDING 146, ROOM 203, AREA B
AGENDA AS IT ACTUALLY OCCURRED - DAY 1

Tuesday, 8 Oct 85

0800-0830	ANNOUNCEMENTS AND ADMINISTRATIVE	Mr. William Augustine, AFWAL/FIGR Col. (Dr.) Grant McNaughten ASD/AESA
0830-0845	WELCOME ADDRESS	Lt. General Thomas H. McMullen, ASD/CC
0845-0910	LOSS OF AIRCRAFT ATTITUDE AWARENESS IMPACT ON USAF	Brig. General Albert L. Pruden, Jr. HQ AFISC/SE, Norton AFB, CA
0910-0955	LOSS OF AIRCRAFT ATTITUDE AWARENESS BY DESIGN & CONFERENCE OVERVIEW	Col. Grant McNaughton, ASD/AESA
0955-1035	VIDEOTAPE - COL. KEHOE'S F-15 INCIDENT & ATTITUDE AWARENESS PROBLEMS IN THE F-15	Maj. Merrill Beyer, ASD/TASCO-A
1035-1100	BREAK	
1100-1125	PILOTS VERTIGO AND ATTITUDE AWARENESS IN THE A-7	Capt. David H. Zayachkowski, Louisa Station, Santurci, Puerto Rico
1125-1200	F-16 SPATIAL DISORIENTATION	Maj. Arthur Fowler, 56TTW, MacDill AFB, FL
1200-1315	LUNCH	
1315-1430	HOW THE BRAIN AND PERCEPTUAL SYSTEM WORKS	Dr. Richard Malcolm, Maltech Research Corp, Ontario, Canada
1430-1500	TWO MODES OF PROCESSING VISUAL INFORMATION	Dr. Herschel Leibowitz Psychology Department Penn State University, State College, PA

1500-1515	VERTICAL DISPLACEMENT SENSITIVITY ACROSS THE HORIZONTAL VISUAL MERIDIAN FOR VARIOUS STIMULUS RATES, DURATIONS, AND LENGTHS	Dr. Richard Haines, NASA-Ames Research Center, Moffett Field, CA
1515-1530	BREAK	
1530-1600	CONTRAST SENSITIVITY FUNCTION IN DISPLAY TECHNOLOGY	Dr. Arthur Ginsburg, VISTECH Inc., Dayton, OH
1600-1630	VESTIBULAR ORGANS IN VERTIGO	Dr. Kent Gillingham, USAFSAM/NV, Brooks AFB, TX
1630-1730	INTEGRATING THE PILOT INTO THE DESIGN PROCESS	Col. David Milam, HQ USAF/RDQ, Washington DC
1730-1930	SOCIAL HOUR	Fly-Wright Club Patio, Bldg 189, Area B

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0830-0850	AIR FORCE INSTRUMENT FLIGHT TRAINING	Lt. Col. William Ercoline, USAF IFC/OP, Randolph AFB, TX
0850-0900	NEEDS OF IFC	Col. Jay Baker USAFIFC/CC Randolf AFB, TX
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1015-1100	FREQUENCY SEPARATION: A THIRD ALTERNATIVE IN THE OUTSIDE-IN/INSIDE-OUT CONTROVERSY	Dr. Stanley Rosco, New Mexico State Univ. and ILLIANA Aviation Sciences Ltd, Las Cruces, NM
1110-1130	HUD PITCH SCALE DESIGN & EVALUATION	Dr. Robert Taylor, MOD, RAF Institute of Aviation Medicine, Farnborough, Hampshire, UK
1200-1310	LUNCH	
1310-1340	ATTITUDE AWARENESS FROM THE US NAVY PERSPECTIVE	Mr. Fredrick Hoerner SY70 Naval Air Test Center, Patuxent River, MD
1400-1440	ROLE OF MANEUVERING FLIGHT PATH	Mr. Frank Watler, Northrop Advanced Systems Division, Pico Rivera, CA
1440-1515	AIRCRAFT LIGHTING CONSIDERATIONS	Mr. Jeffrey Craig, AAMRL/HEA
1515-1535	BREAK	

1535-1600	GLARE AND REFLECTIONS IN DAY AND NIGHT FLYING	Dr. Lee Task, AAMRL/HEF
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0945-1000	MAGIC OVERVIEW	Dr. John Reising, AFWAL/FIGRB
1015-1035	ROLE OF VIRTUAL DISPLAYS	Dr. Thomas Furness, AAMRL/HEA
1035-1100	VIRTUAL UMBRELLA ATTITUDE DEPICTION	Emily Howard, Dept. Psychology, UCLA, Los Angeles
1100-1130	MODIFICATION POTENTIAL FOR HUD CONTROL PANEL	Mr. William Augustine, AFWAL/FIGR and Mr. Richard Newman, Crew System Consultants, Yellow Springs, OH
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PREFACE

This document constitutes the proceedings of the Aircraft Attitude Awareness Workshop jointly sponsored by the Air Force Wright Aeronautical Laboratory Crew System Development Branch (AFWAL/FIGR), and the Aeronautical Equipment Life Support Systems Program Office (ASD/AES).

Attendance included over 200 invitees representing the following:

Government: Civilian and military employees of the Canadian Forces, NASA, Royal Air Force, USAF, USMC, and USN.

Industry:

Airframers: Douglas AC, GD, Grumman, Lockheed, Mac Air, Northrop, Rockwell International.

Avionics: CAE Electronics, Ferranti, Garrett, GEC-Avionics, Hughes, J.E.T. Electronics, Kaiser Electronics, Lear-Siegler, Rank, Raytheon, Smiths Industries, Sperry, Sundstrand, Texas Instruments.

Other: Analytics, Batelle Labs, Burnesst Engineering, Calspan, Condra Aviation, Crew Systems, Env. Res. Institute of Michigan, Gehring Associates, John Sheets Designs, Maltech Research Corporation, McCauley-Brown, Perceptual Dynamics Research, Systems Research Lab, Vistech, Watkins Association.

Universities: New Mexico State, Ohio State, Penn State, UCLA, Wisconsin, Wright State.

We would like to take this opportunity to thank the following people whose support was so essential to the success of this workshop:

Mr. Frank Scarpino, AFWAL/FIG, who funded most of the conference.

Dr. Tom Furness, AAMRL/HEA, who funded several of our speakers and who spoke himself.

Mr. Pete Lovering, Midwest Systems Research, who provided astute guidance, handled many of the arrangements, and participated as a speaker.

Ms. Evelyn Bailey, Dr. McNaughton's secretary, who handled many of the arrangements before and during the workshop, then painstakingly transcribed tape recordings of the sessions for these proceedings. Her contributions were truly monumental.

Ms. Kathryn Sinkwitz, Mr. Augustine's secretary, who ably shared pre-conference arrangements with Ms. Bailey.

We would also like to thank Ms. Andrea Brown for her talented efforts in preparing the final manuscript.

William Augustine
AFWAL/FIGR

and

Grant B. McNaughton
COL USAF (MC) CFS
ASD/AESA
Wright-Patterson AFB, Ohio

1 August 1986

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XXVI, XXXVI, 3-1-1 through 3-1-8, 3-4-1 and 3-4-2.

INTRODUCTION AND SUMMARY

Several of our newer state-of-the-art fighter-attack aircraft, while well-suited to the day VMC role, create significant problems for the pilot when flown at night or in IMC. Much of the problem stems from the fact that designers have not taken into consideration how the pilot functions or what he needs in order to maintain basic attitude awareness. Thus on one hand, these aircraft contain features which tend to mislead, confuse, or disorient the pilot, while on the other hand they fail to provide adequate references for coping - for maintaining or regaining aircraft attitude awareness.

It is our responsibility to analyze these problems, to determine whether cost-effective remedies exist for our current fleet, but perhaps even more importantly, to insure that these problems not be perpetuated in future aircraft. For, unless the priorities are properly established, many of these ultra-expensive aircraft and their crew will needlessly be lost in training mishaps. the first priority is aircraft control, the ingredients of which are awareness of attitude, altitude, airspeed, and vertical velocity.

This workshop considered aircraft attitude awareness not only in the context of spatial disorientation, in which the pilot is aware of an orientation problem, but also in the context of spatial "misorientation," in which the aircraft has subtly attained an attitude of which the pilot is unaware. Furthermore, in view of the preponderance of mishaps due to Controlled-Flight-Into-Terrain (CFIT), considerable attention was devoted to altitude awareness, collision warning and avoidance systems, automatic recovery systems, and G-limiter override capability.

The workshop developed a number of findings and recommendations summarized below:

> To avoid collisions with the surface, the pilot needs inputs to sensory channels other than the focal visual system. Properly designed auditory and proprioceptive interfaces have the potential to redirect the pilot's attention to his flight path in time to initiate correction. Failing this, the aircraft should attempt to auto-recover.
>
> To maintain or regain aircraft attitude awareness, the pilot requires visual displays that are dedicated and properly integrated within the cockpit. There are currently three basic components: the primary and standby attitude indicators, and the head-up display (HUD); and there is potential for emerging technologies such as helmet mounted displays and possibly three-dimensional sound. The hub of aircraft attitude awareness is a large primary dedicated attitude display (PDAD) centered high in the instrument panel and located just beneeth the HUD. Its purpose is to provide continuously and instantly the immediate big attitude picture to the pilot's basic orientation channel, the ambient

visual mode. It should be visible when the pilot's attention is directed to the HUD. The second component is the head-down attitude display (formally the Standby Attitude Indicator or SAI). This should also be in the midline and sufficiently low to permit its use in the presence of ambient visual mode distractions, such as moving glare and reflections off the canopy, or false horizons. The third component providing attitude information is the HUD, yet the HUD is not an attitude indicator. The potential exists to improve the HUD as an attitude alerting device, directing the pilot to refer to the PDAD. Suggested improvements included the addition of a zenith pointer to the Flight Path Marker to provide a better roll cue, and radically altering the pattern between positive and negative Flight Path Scales to provide better pitch cues.

Current fighter/attach aircraft are poorly suited to the enhanced night role. Remedies must consider the compromised nature of the pilot who flies at night. As a minimum, aircraft need better attitude references, to include a large PDAD, critical control parameters formatted for instant unequivical recognition, improved cockpit and instrument lighting, less canopy glare and reflections, better formation lighting, and no false horizons.

Several training issues emerged: basic instruments, the use of the HUD's as instruments, the use of attention and the proper use of vision. The USAF/IFC should be supported in the acquisition of a training aircraft equipped with a programmable HUD for instrument research and training.

Virtual displays projected onto the visor as helmet mounted displays offer great potential for a variety of purposes, especially aircraft attitude awareness. This technology should be pushed vigorously.

There have been several instances in F-15's where the recovery from a spatial disorientation incident required the pilot to over-G his aircraft. At least one F-16 might similarly have been saved had the pilot had access to every G available. Consideration should be given to the incorporation of a G-limiter by-pass as an emergency override in aircraft such as the F-16.

The enormous information processing capability of sensory channels such as the ambient visual mode, hearing, and proprioception is underutilized. This thrusts the task of maintaining awareness of critical aircraft control parameters upon the focal visual mode, tending to overload it. Strong emphasis should be placed upon displays which can be processed by non-focal visual mode sensory channels.

An innovative audio-technology known as three-dimensional sound appears to offer promise in such areas as warnings and alerts, localization of objects in space, and possibly aircraft attitude awareness. Research and development should be pushed.

The noise in modern cockpits is commonly such as to hamper effective communications and potentially helpful auditory cues. A technology is currently under development that can effectively reduce relatively steady state background noise by a significant amount, improving the audio environment for sounds that matter. Research and development efforts in this area should continue.

There are times when a pilot requires certain information yet does not want to look away from his primary task to obtain it. A voice call out of such information upon command would be very useful, and could include parameters such as attitude, altitude, airspeed, VVI, fuel state, rounds count, weapons mode selected, etc.

WORKSHOP FINDINGS AND RECOMMENDATIONS

1. ALTITUDE AWARENESS

Current fighters commonly lack adequate warnings and alerts to altitude; i.e. altitude awareness is even more critical than attitude awareness, in view of the preponderance of controlled-flight-into-terrain (CFIT) mishaps (Fig 1). These mishaps are due primarily to lack of awareness, failure to monitor flight path, distraction, etc, though they may often be set up by misperception of altitude AGL or of vector convergence with terrain. The pilot needs something to wake him up, to redirect his attention to his flight path, as well as an absolute height gauge.

RECOMMENDATION 1:

- Aural Ground Proximity Warning System
- Radar Altimeter
- Push development of more effective audio warnings/ alerts to impending collision with the surface (e.g. 3-dimensional sound)

2. ATTITUDE DISPLAYS

Attitude Displays are inadequate. They are too small and too deep in the cockpit. Under suboptimal lighting, they may be subject to misinterpretation. Current configuration delays to rapid transition from outside to inside and inhibits the wingman from sneaking a peek during close formation. It hampers the pilot from maintaining his own big attitude awareness picture, especially when his attention is focused on the head-up display (HUD). It impedes the recognition of unusual attitudes (in cases of unrecognized spatial disorientation or misorientation). Furthermore, it impairs coping with spatial disorientation (SDO) and unusual attitudes. The obvious solution is to utilize the space below the HUD (presently the up front control panel) for a large, prominent primary dedicated attitude display. Several methods for accomplishing this were suggested: one involved the projection of an attitude depiction onto the up front control panel (UFC). Others were to take advantage of emerging flat panel technologies for the PDAD, and consider touch sensitive overlays for the UFC, or consider displacing the UFC to the left side of the HUD container for access by the pilot's left hand.

Reasons for a prominent PDAD are as follows:

- Keep Pilot Oriented
  - Maintain big picture when attention focused on HUD
  - In conditions of potential spatial disorientation/misorientation
  - When pilot compromised, e.g., fatigue
- Provide Ready Attitude Reference Near HUD/Eye Line
  - For pop-up/pull-downs
  - Facilitate transition from outside to inside
  - Enable wingman to maintain own AAA while flying formation
- Reduce Cockpit Workload
- Aid Recognition of Unexpected Inadvertent Unusual Attitude and Facilitate Coping
- Facilitate Coping with Frank Spatial Disorientation or Pilot's Vertigo

RECOMMENDATION 2:

- Large, prominent, primary dedicated attitude display (PDADP, dedicated full time, immediately below the HUD (Fig 2 A, B, and C).

3. HUD IMPROVEMENTS

The HUD is not an attitude indicator, nor should it ever be, although it does provide some information regarding attitude. What the HUD needs to be able to do regarding attitude, is alert the pilot when to refer to the primary dedicated attitude display (PDAD) which, ideally, should be located immediately below the HUD. To improve the HUD as an attitude alert requires at least two changes: one to the Flight Path Marker (FPM) and the other to the pitch scales, (Figs 4 & 5).

The basic problems with the HUD, as far as attitude is concerned, are that it does not tell the pilot, at a glance, whether he is upright or inverted, or whether he is pitched above or below the horizon, or to what general extent he is pitched. Humans are basically patterned recognizers, and since the general pattern of the pitch scales are symmetric about the horizon, it is possible to confuse an inverted dive for an upright climb (Fig 3).

This was recently illustrated in the full mission F-16 LANTIRN simulator by subjects participating in a certain study. The intention of the subjects was to perform a pop-up pull-down delivery (by popping, rolling inverted, pulling down, and rolling out upright to bomb the target). In repeated instances, subjects would become so engrossed in the target that they would forget they had rolled out upright. Attempting to sort it our by looking at the HUD was of no help. The flight path scale provided no innate sense of up. Besides, it was moving too rapidly for interpretation. In these instances, thinking himself to still be inverted, the subject would roll again (to inverted) and pull into the ground. It is to avoid just such errors that we should strive to provide a roll cue on the Flight Path Marker, such as a Zenith or Vertex Pointer (Figure 4).

Another most dangerous aspect is that the HUD does not instantly distinguish between climbs and dives. The problem lies with the global symmetry of the flight path scales (FPS), i.e. both the positive and negative FPS's have the same general shape with horizon-pointing tails in the same location. Though generally a useful cue, the solid line for positive pitch and dashed for negative pitch does not always register, especially in a dynamic situation, but also occasionally in a static one as well. For example, it is possible to confuse an inverted dive for an upright climb. Angling the FPS's like chevrons forming a channel toward the horizon helps locate the horizon, but if the global pattern remains symmetrical, it is still possible to confuse an inverted dive for an upright climb. For this reason, it is urged that attempts be made to maximize the differences in the overall FPS pattern between positive and negative. For suggestion see Fig 5 .

RECOMMENDATION 3: Improve HUD as an attitude alerting device by:

- FPM: add vertex pointer (e.g. Fig 4)
- Pitch scales: radically change pattern from positive to negative and within negative (e.g. Fig 5); consider color as a redundant cue.

4. NIGHT-WEATHER ROLE CONSIDERATIONS

The night-weather role requires special considerations, both for the pilot and for the aircraft. For the pilot, fatigue is a given; reactions are slowed, perceptions impaired, and the pilot is more subject to illusions, particularly those of false motion and those of false horizons; he is more susceptible to disorientation, distraction, channelized attention, and loss of the sense of the passage of time. Regarding aircraft considerations, present single-seat fighters are not adequate for the night-weather role. Their bubble-shaped canopies gather glare and reflections, movement of which across the canopy creates distractions, or worse, the disorienting sensation of self motion (vection illusion or Star Wars effect, Fig 6). At night, the glare and reflections impede outside viewing, impair the acquisition of a valid external orientation cue (true horizon or surface), and hamper the ability to distinguish false horizons (Fig 7). Quite commonly, the light sources for the glare and reflections are from within the cockpit, where little, if any, attempt has been made at proper shielding. The routes of information transfer regarding critical control parameters such as attitude, airspeed, and altitude are inadequate. Visual displays are not always formatted for instant unequivocal interpretation, nor are they adequately illuminated, lacking individual rheostats. Thus they promote spatial disorientation, or worse, a more subtle form of unrecognized disorientation (misorientation), more lethal because it fails to alert the victim that anything is amiss. Yet they fail to provide the information necessary for recognition and coping in a quickly recognizable, unmistakable format.

Inadequacies in lighting apply not only to the cockpit and instruemtns, but very much so to formation lights. Present schemes deny the wingman adequate recognition of lead's distance, relative heading and relative attitude. Proper attention has not always been paid to the hazardous aspects of certain external lights, e.g. the aerial refueling light generating a false horizon.

RECOMMENDATION 4:

For the night role, aircraft need the following as a minimum:

- Better attitude references, to include a large primary dedicated attitude display (PDAD) high in the center of the instrument panel
- Critical control parameters formatted for instant unequivocal recognition
- Better cockpit and instrument lighting
- Efforts to minimize/eliminate canopy glare and reflections
- Better formation lighting
- No false horizons

5. TRAINING

Several training issues emerged: basic instrument training, the use of HUD's as instruments, attention, use of vision, and G-tolerance.

Review of certain recent mishaps has revealed as causes, insufficient mastery of basic instruments. Much of this is attributed to a de-emphasis of instrument training, as illustrated by the closure of the Instrument Pilot Instructor School (IPIS), and the curtailment of instrument sorties by ATC, upon the premise that simulators would suffice.

Despite the presence of HUD's on many of our state-of-the-art fighters, no formal program has been undertaken to train their use in instrument conditions. The evolution of HUD's as flight control instruments presents a challenge for Air Force pilots and designers: that of determining the optimum layout to integrate head-up and head-down (conventional) displays. HUD's with unvalidated instrument capability have been integrated into the same cockpits that have relegated proven head down displays to less accessibly visible locations deeper in the cockpits. There is concern that the changes in current cockpits may be at the expense of maintaining attitude awareness and aircraft control in conditions of reduced visibility. The situation may worsen with increasing mission complexity and the desire to place top priority on displays associated with use of the aircraft as a weapon system. While no one disputes the importance of ordnance delivery, the top priority should always be to maintain aircraft control.

The USAF needs to examine the complete instrument training program for all pilots and recommend methods to better prepare users to cope with their increasingly higher work-load situations. The central agency to develop such training programs should logically be the USAF Instrument Flight Center (IFC) at Randolph AFB, TX. Logic would also dictate that the IFC further conduct the research on which to base such training programs. In order for the IFC to be able to do this, they will need special equipment. It is for this reason that we strongly recommend IFC acquire programmable HUD-equipped training aircraft for purposes on instrument training development and for operational evaluation.

In addition, it should be recognized that design impacts training. The old "T" was relatively simple compared to what we now have. Since IFC is the logical agency to develop instrument training, it would make sense to include them in the cockpit instrument design and display approval process as well.

Regarding the training of attention and use of vision, one attendee stated that both of these were possible and, in fact, had been done during World War II. He was referred to IFC for follow-up.

Regarding G-tolerance, the connection between that factor and aircraft attitude was brought out. During gradual G onset the peripheral visual fields contract causing tunnel-vision, grayout, or blackout. Such visual narrowing may permit the attainment of undetected attitudes. This factor may be reduced through proper anti-G training.

RECOMMENDATION 5-1: Improve training of basic instruments:

- Support IFC to resurrect IPIS
- Support ATC to increase instrument training sorties

RECOMMENDATION 5-2: Train use of the HUD: support IFC to acquire a HUD-equipped training aircraft for development of appropriate displays, training, and operations.

RECOMMENDATION 5-3: Support training measures to improve G-tolerance, because of its beneficial effects on the preservation of ambient vision on orientation.

RECOMMENDATION 5-4: Push the investigation of methods to improve attention and the use of vision.

6. AUTO-RECOVERY/CRASH RESISTANCE

Should the pilot become incapacitated for whatever reason physically from a cardiac or neurological event, physiologically from G-induced loss-of-consciousness or hypoxia, pharmacologically from chemical warfare agents or their antidotes, psychologically from severe disorientation/vertigo, or visually from laser/nuclear flash-blindness, the aircraft should resist crashing and recover itself. The state-of-the-art is rapidly approaching the point of being unable to afford to do otherwise in terms of airframes, pilots, and litigation. The system should be capable of actuation actively ("Panic Button") or passively.

RECOMMENDATION 6: Push the development of crash-resistant flight control systems and auto-recovery.

7. VIRTUAL DISPLAYS

Virtual displays projected onto the visor as helmet mounted displays (HMD) (Fig 8) offer great potential for a variety of purposes, especially in aircraft attitude awareness. An example is the "Virtual Umbrella" which provides for the surface, a checker-board for an unmistakeable ground reference, and for the sky, a series of vertical lines spaced at certain intervals which join at the vertex, like the ribs of an umbrella (Fig 9 A & B). Regardless of where the pilot looks, the virtual umbrella keeps him oriented, just like being VFR.

Similarly, virtual cockpits offer great promise in overall situation awareness.

A by-product of the HMD is potential protection against laser/nuclear flash-blindness.

RECOMMENDATION 7: Vigorously push the development of virutal helmet mounted display technology.

8. G-LIMITER BY-PASS

There have been at least three instances in F-15's where the recovery from a severe spatial disorientation incident required the pilot to over-G his aircraft. One such instance was that of Col Nicholas B. Kehoe, former Wg DO (now Wg CV) 1 TFW, Langley AFB, VA, whose episode of 11 February 1985 was recorded on VTR and shown at this conference, with his blessing. There has also been at least one instance in a F-16 in which a G-limiter bypass would have saved the aircraft from hitting the ground. (In that instance, which killed the pilot, the HUD-VTR survived the crash and makes for a dramatic review.) The consensus of this conference was that there should be some way of overriding the limiter in an emergency to get all the G's the aircraft is capable of generating, even at the expense of structural damage. (A bent wing is preferable to a smoking hole.)

RECOMMENDATION 8: Consider incorporation of G-limiter by-pass as an emergency override in aircraft such as the F-16.

9. NON-FOCAL VISUAL MODE SENSORY CUES

The enormous processing capability of non-focal visual mode sensory systems are presently under-utilized.

- Auditory & Tactile cues

Current aircraft lack adequate tactile and auditory cues to airspeed making it easy to inadvertently get too slow, into stalls, or into sink rates unawares. Feel of the aircraft is no longer available as a portion of the critical triangle of agreement regarding basic aircraft control; nor are audio inputs. Auditory cues are considered necessary for airspeed (and aircraft) control, especially in aircraft lacking such tactile cues, such as the F-16. The same applies to certain instances of flight control activity; eg. the speed brakes on the A-10 provide no tactile nor auditory cue when deployed, with serious implications for situations of reduced thrust.

RECOMMENDATION 9-1: Incorporate auditory/tactile cues to critical parameter controls.

- Ambient mode displays

Present displays are designed to be processed only by the focal visual mode thus tending to overload it. Better use of the processing capability of the ambient visual mode could be made by the proper formatting of displays: eg. patterned analog format for parameters such as airspeed and altitude. Such parameters lend themselves well to the moving tape format (Fig 10 A & B). For suggestions see Figs 11 & 12.

RECOMMENDATION 9-2: Press for development of displays for critical parameters (airspeed, altitude) that can be processed by the ambient visual mode.

10. THREE-DIMENSIONAL SOUND:

A technique known as 3-D sound appears to offer promise in several areas:

Warnings and alerts when it is imperitive to get the pilot's attention, eg. to avoid collision with the surface, another aircraft, or a missile. In such instances, the quality and intensity of the warning sound would be such that it would appear to be coming from within one's ear or head, and thus impossible to ignore.

To locate objects, either inside the cockpit, such as a fire/caution-light, or outside the aircraft, such as an element mate, control agency, bogey, or hostile missile on the way. For example, if your wingman calls from your 8 o'clock high, telling you where to look. Same with the hostile missile: the rattlesnake tone comes from the direction of the missile, directing your search and preparing you for the proper direction to break.

Sound has historically provided excellent cueing to one critical aircraft control parameter. Perhaps it can also be used to aid cueing to other critical control parameters as well, such as attitude (vertex tone?) and closure with the surface.

RECOMMENDATION 10: Press the development of audio technologies, such as 3 dimensional sound, for use in warnings and alerts, in localization, and in maintaining aircraft control.

11. STANDBY ATTITUDE INDICATOR

Wide separation of the Standby Attitude Indicator (SAI) from the primary attitude indicator precludes the immediate recognition of a mismatch between the two and upsets one's composite instrument cross-chick should transition become necessary. It should also be as reliable as possible to avoid misleading the pilot. It should be centered below the Primary Dedicated Attitude Display (PDAD) to serve as a head-down attitude display, and sufficiently large to be included in the basic instrument cross-check. Centering it between the standby airspeed and altimeter displays also preserves the basic relationship ingrained through training. View should not be blocked by objects such as the stick.

RECOMMENDATION 11: Standby Attitude Indicator should be reliable, large, centered below the PDAD, located with the standby airspeed and altimeter displays, and fully visible.

12. NOISE-CANCELLING HEADSET

A technology is currently under development (by AAMRL/BBD) to reduce noise in the headset. A microphone in the headset picks up the noise signal, phase reverses it and plays it back, cancelling out about 20 db. Works quite well for more or less steady state background noise, such as that from the engine, environment control system, or avionics equipment. Shows promise in improving the audio environment for sounds that matter.

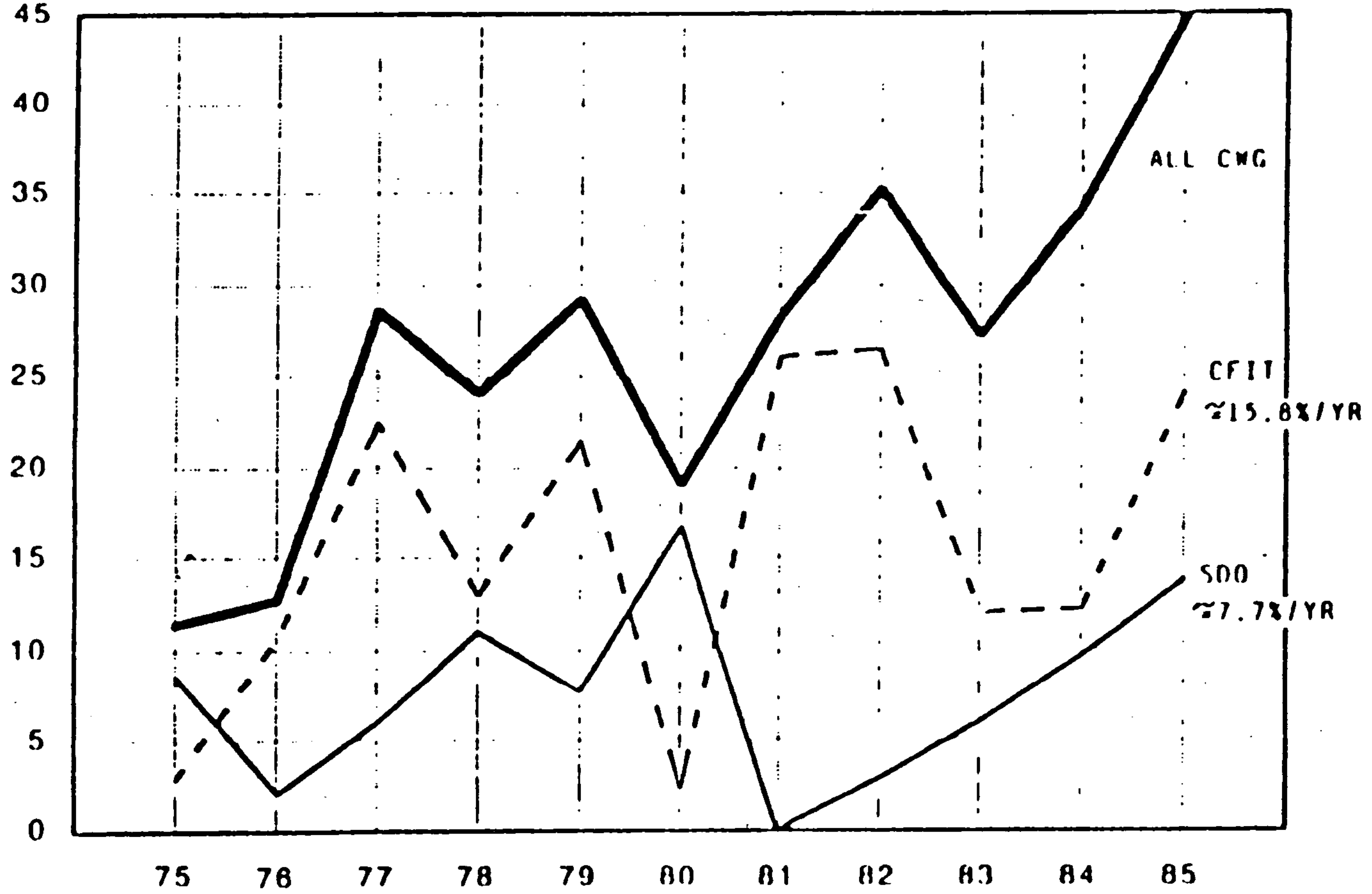
RECOMMENDATION 12: Push the development of noise-cancelling technologies, such as that currently underway at AAMRL.

13. AUDITORY CALLOUT OF SELECTED INFORMATION

There are times when a pilot needs to know certain information yet does not want to look away from his primary task to obtain it. For example, if his attention focussed upon another aircraft that is difficult to keep in view, he might resist looking away, even momentarily, for fear of being unable to reaquire tally. In such instances, it would be highly desirable to have the aircraft speak to him, providing him the information he wants on command. Such information should be pilot-selectable, and could include, but not be limited to: airspeed, altitude AGL, fuel state, attitude, rounds-count, ordnance mode selected, etc.

RECOMMENDATION 13: Voice callout of certain information on command, selectable by the pilot.

COLLISIONS WITH GROUND - % OF OPS CLASS A MISHAPS
1 JAN '75 - 4 OCT '85 (AFISC)

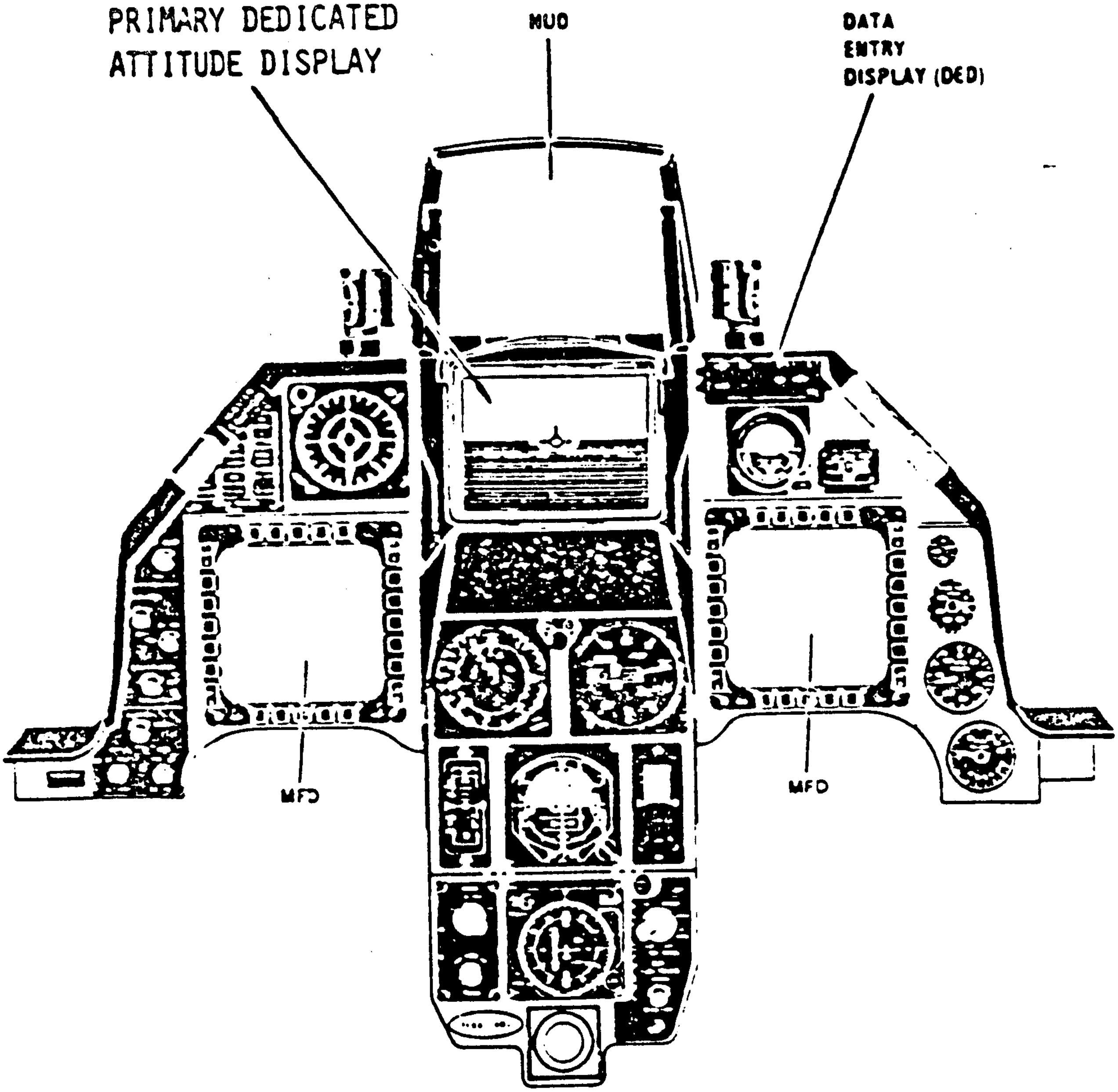


%	75	76	77	78	79	80	81	82	83	84	85
CWG	11.4	12.8	28.6	24.1	29.2	19.1	28.3	35.3	27.3	34.2	44.9
CFIT	2.9	10.6	22.5	13.0	21.5	2.4	26.1	26.3	12.1	12.2	24.1
SDO	8.6	2.1	6.1	11.1	7.7	16.7	0	2.9	6.1	9.8	13.8

A1-142-86COLLISION

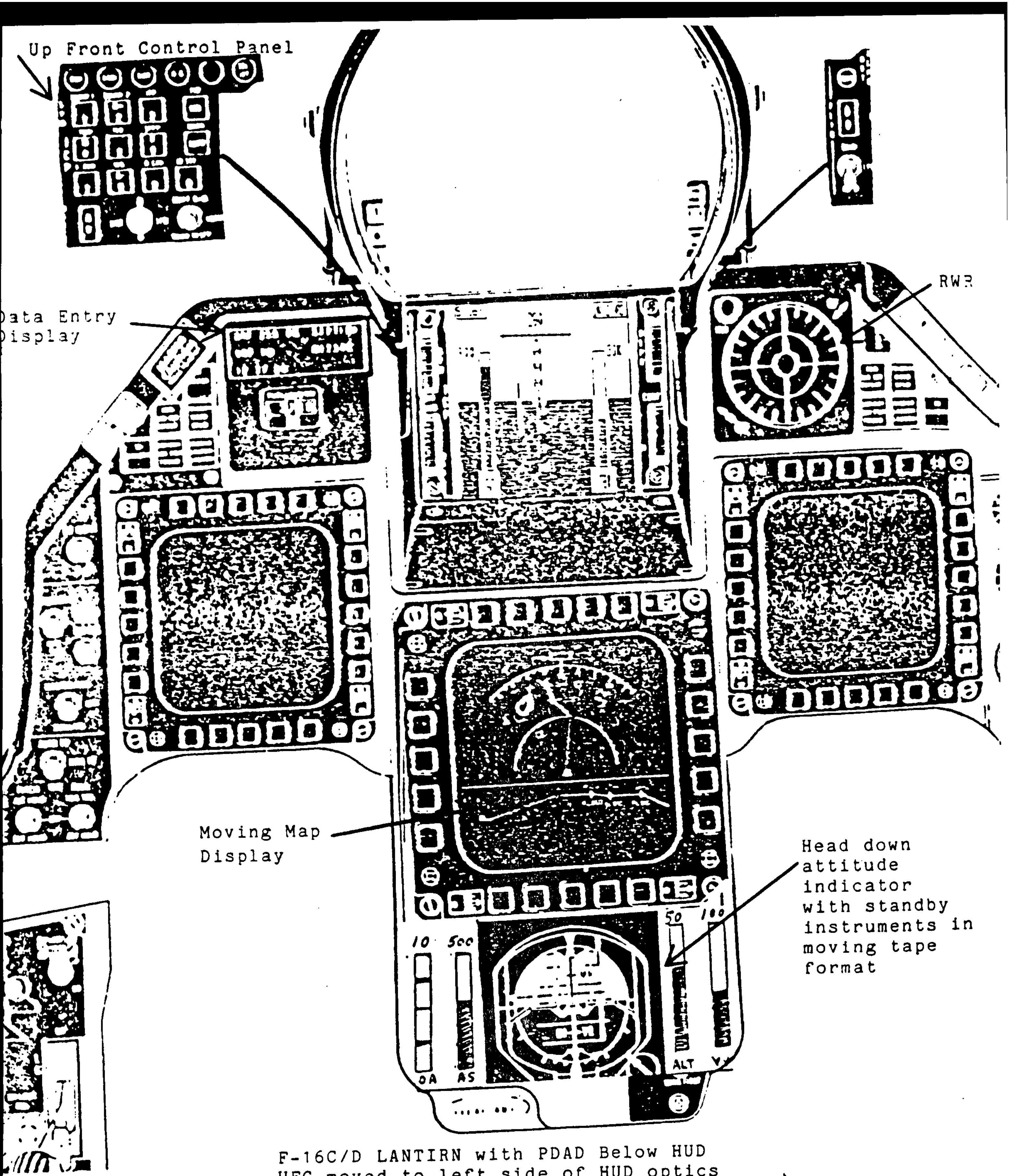
Figure 1

F-16C



C DF

Figure 2 A



F-16C/D LANTIRN with PDAD Below HUD
UFC moved to left side of HUD optics
container, molded to left hand grip.
DED beneath left glare shield, RWR
beneath right glare shield.

Figure 2 B

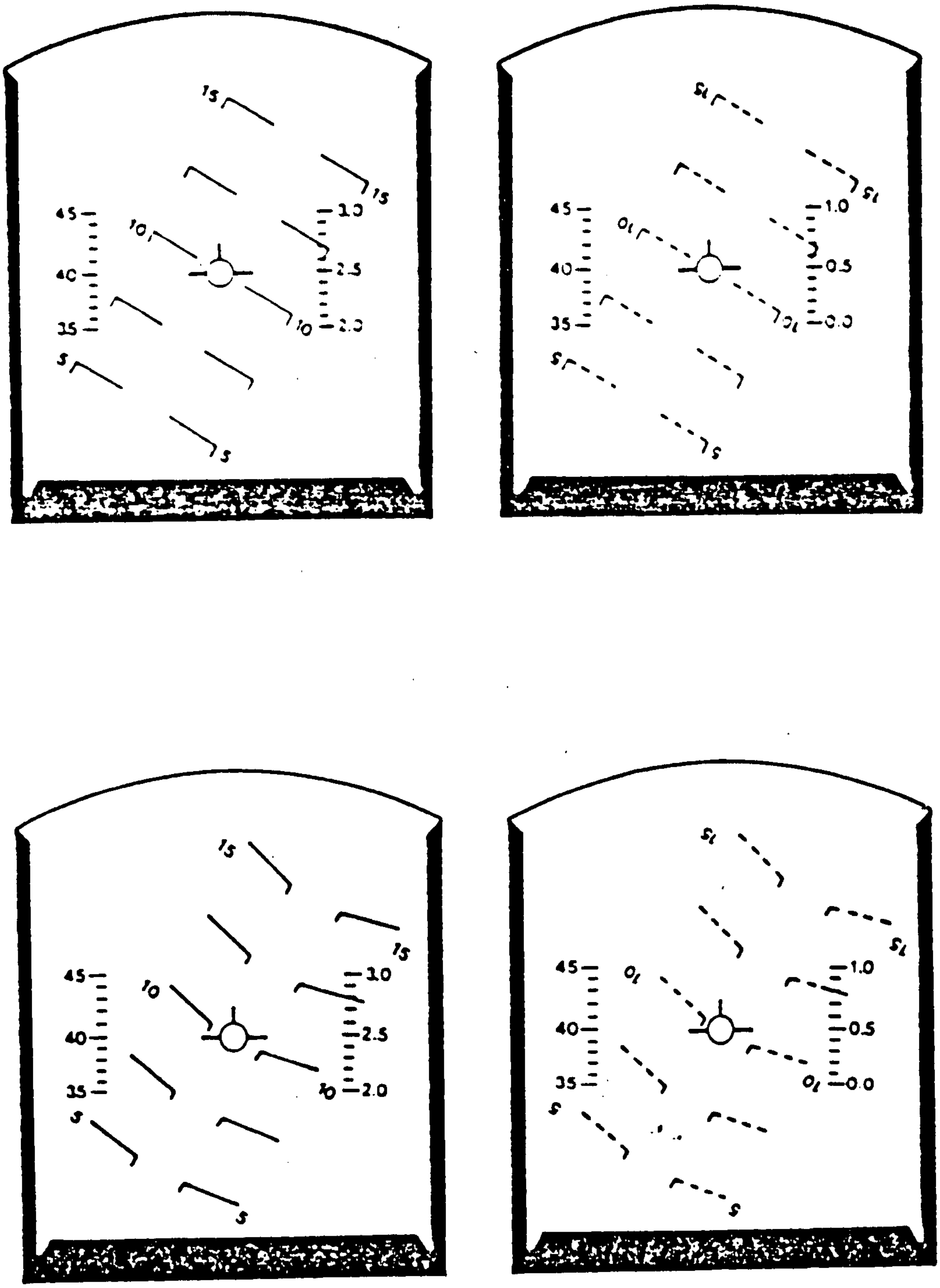

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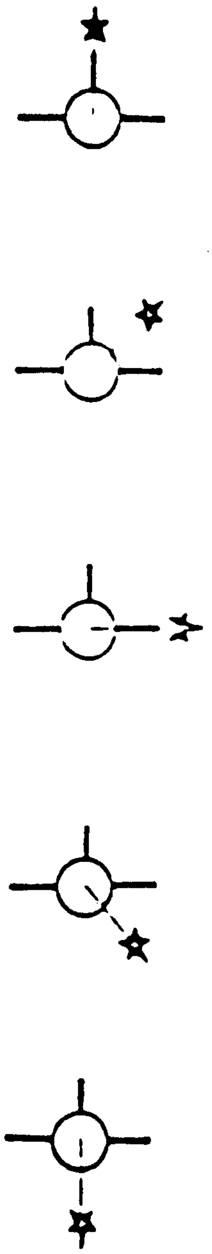
Figure 3



HUD FLIGHT PATH MARKER
SHOWING VERTEX POINTER
Figure 4

HUD PITCH SCALE SHOWING
RADICAL CHANGES FROM POSITIVE
TO NEGATIVE & WITHIN NEGATIVE

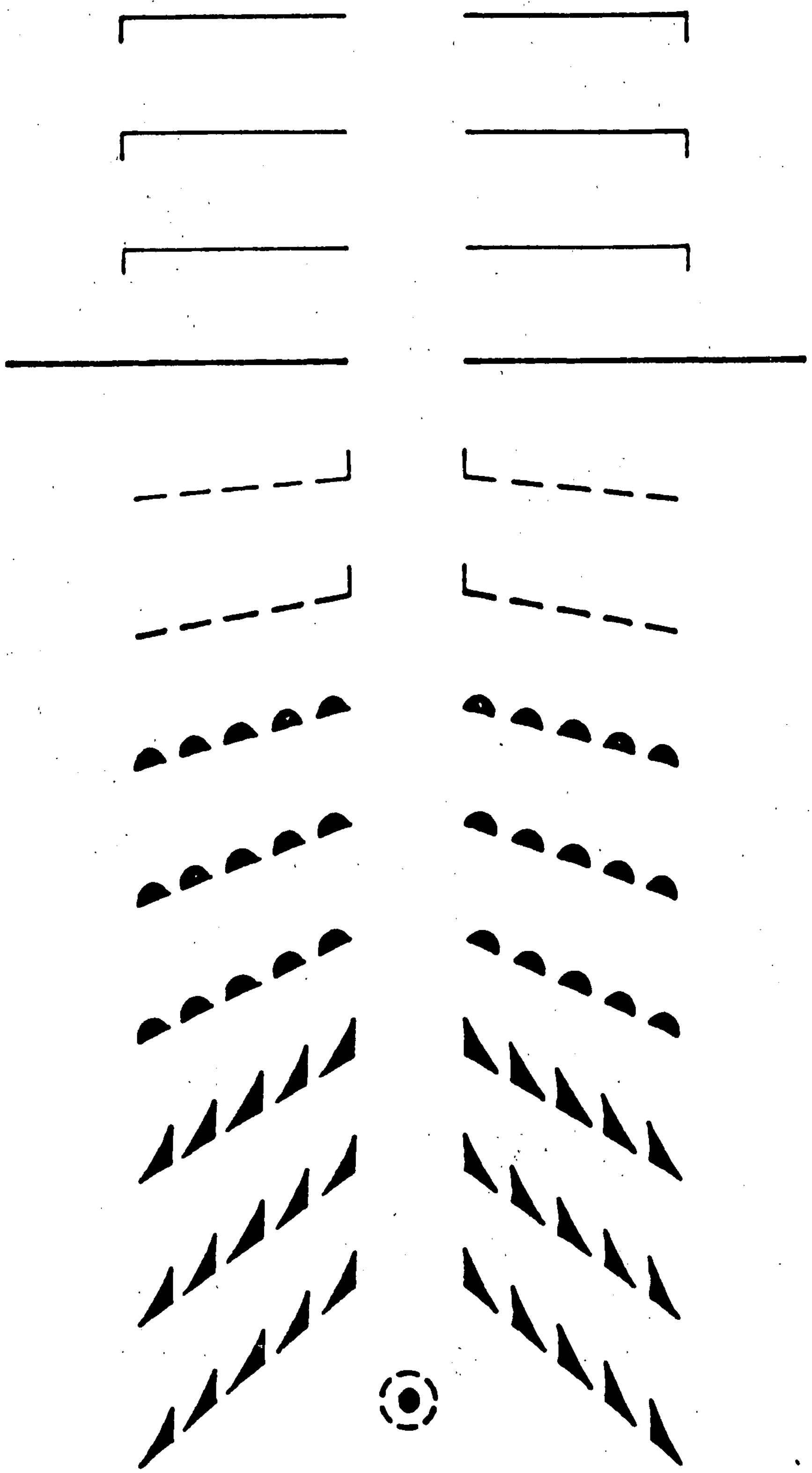
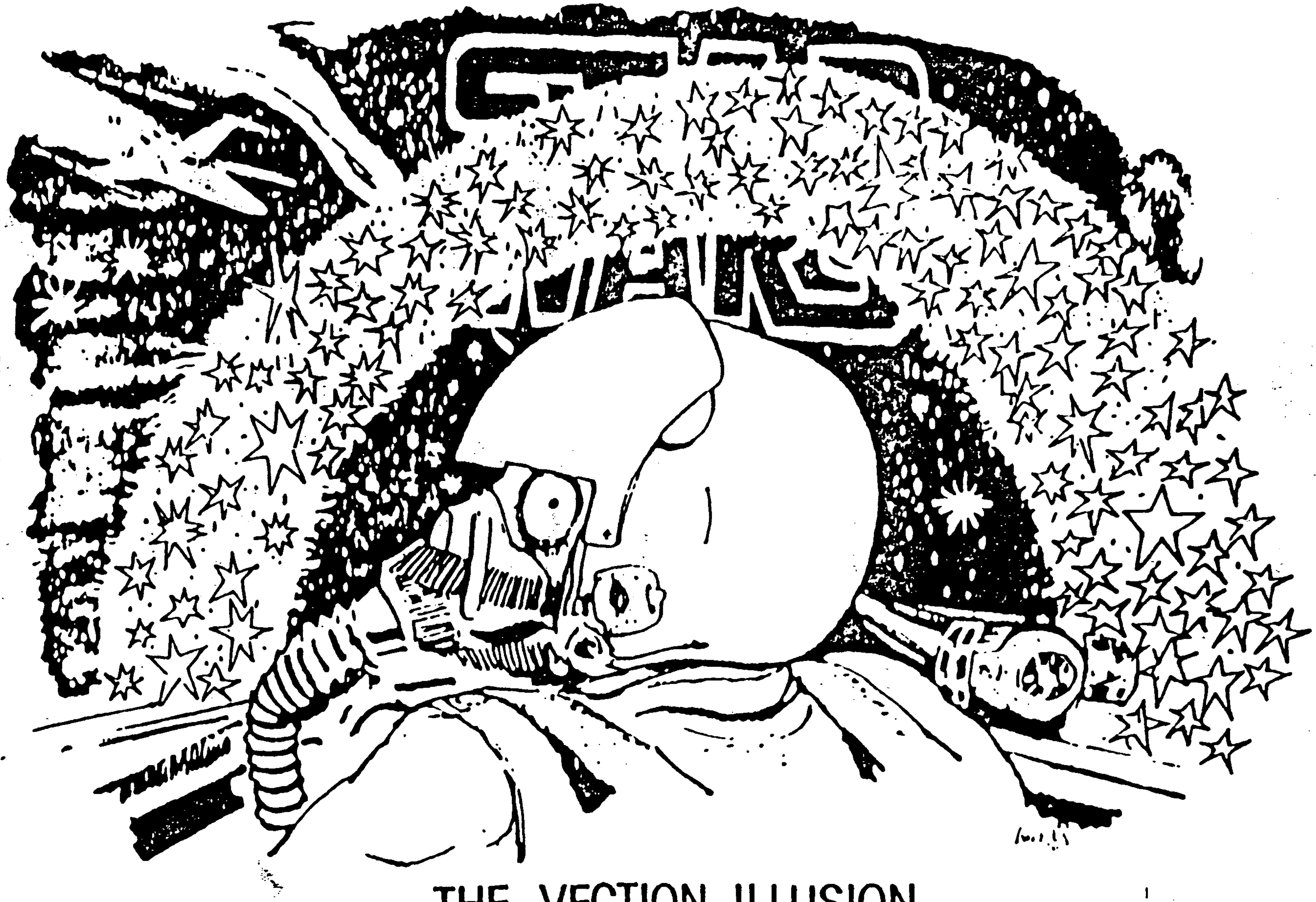
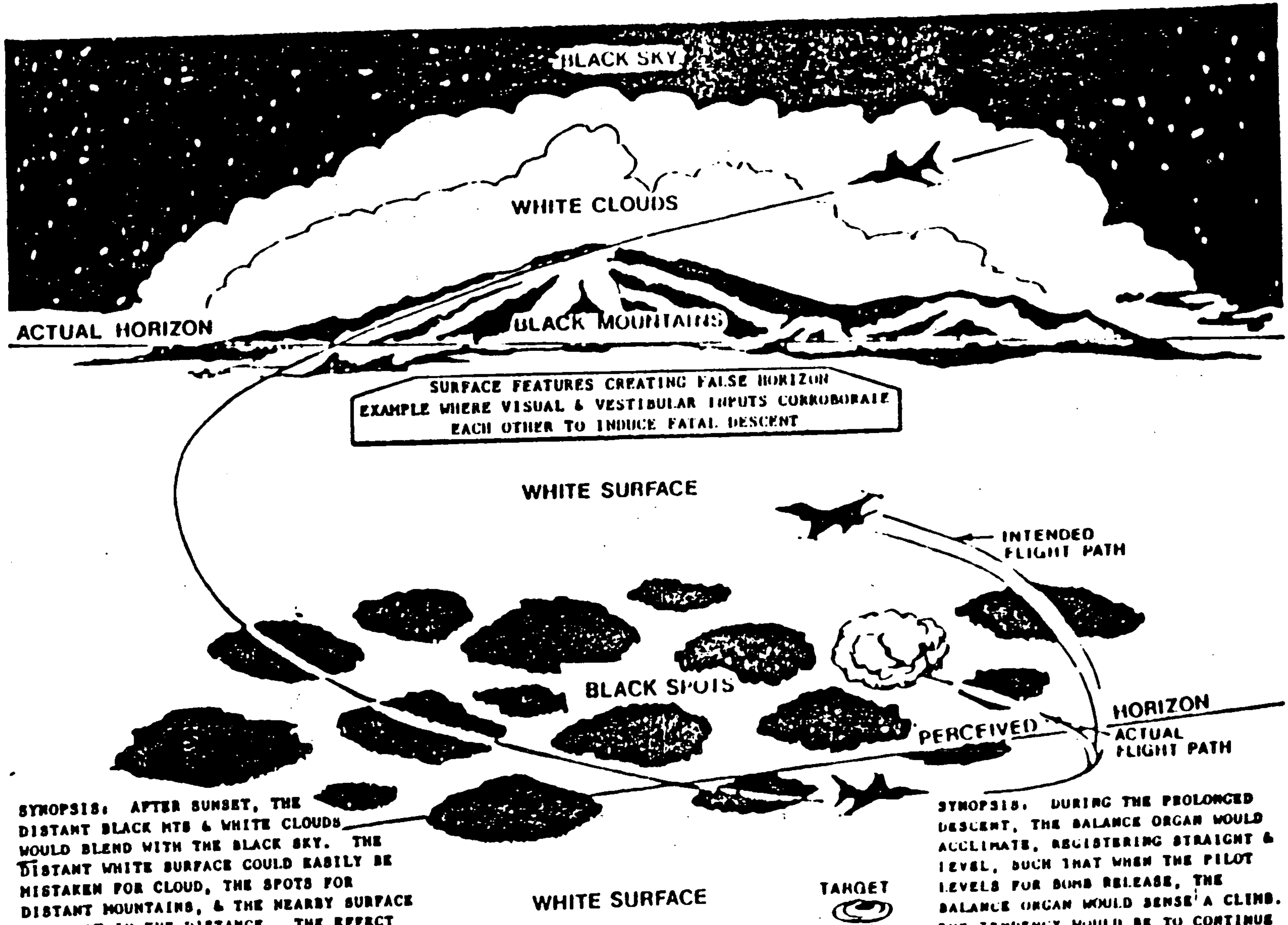


Figure 5

Figure 6



THE VECTION ILLUSION

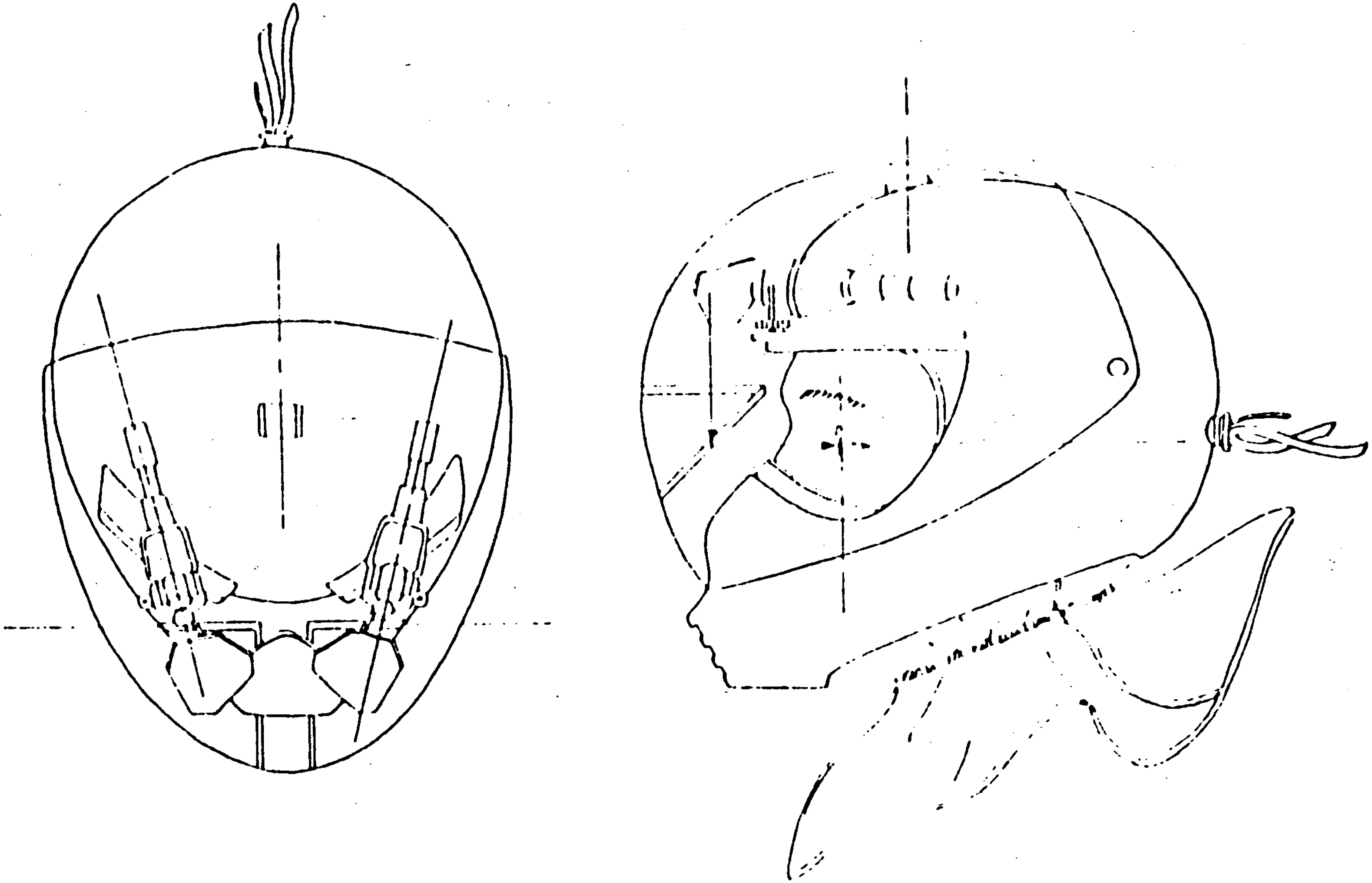


SYNOPSIS: AFTER SUNSET, THE DISTANT BLACK MTS & WHITE CLOUDS WOULD BLEND WITH THE BLACK SKY. THE DISTANT WHITE SURFACE COULD EASILY BE MISTAKEN FOR CLOUD, THE SPOTS FOR DISTANT MOUNTAINS, & THE NEARBY SURFACE FOR THAT IN THE DISTANCE. THE EFFECT WOULD BE TO DISPLACE THE HORIZON AS SHOWN.

SYNOPSIS. DURING THE PROLONGED DESCENT, THE BALANCE ORGAN WOULD ACCLIMATE, REGISTERING STRAIGHT & LEVEL, SUCH THAT WHEN THE PILOT LEVELS FOR BOMB RELEASE, THE BALANCE ORGAN WOULD SENSE A CLIMB. THE TENDENCY WOULD BE TO CONTINUE THE DESCENT.

Figure 7

CONCEPTUAL REPRESENTATION OF A MEDIUM FIELD OF VIEW HELMET MOUNTED DISPLAY



HE 84 4-152

Figure 8

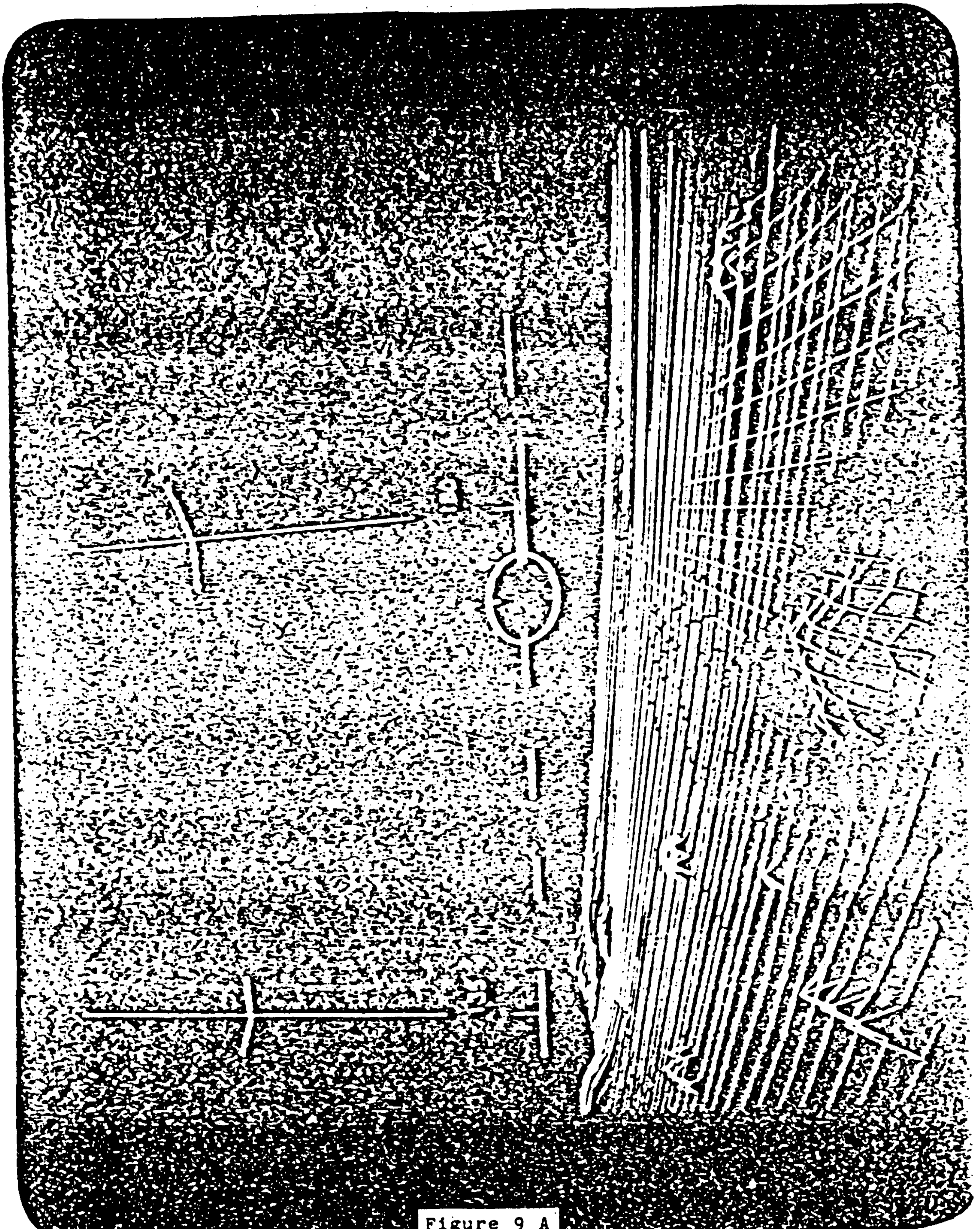


Figure 9 A

XXXIII

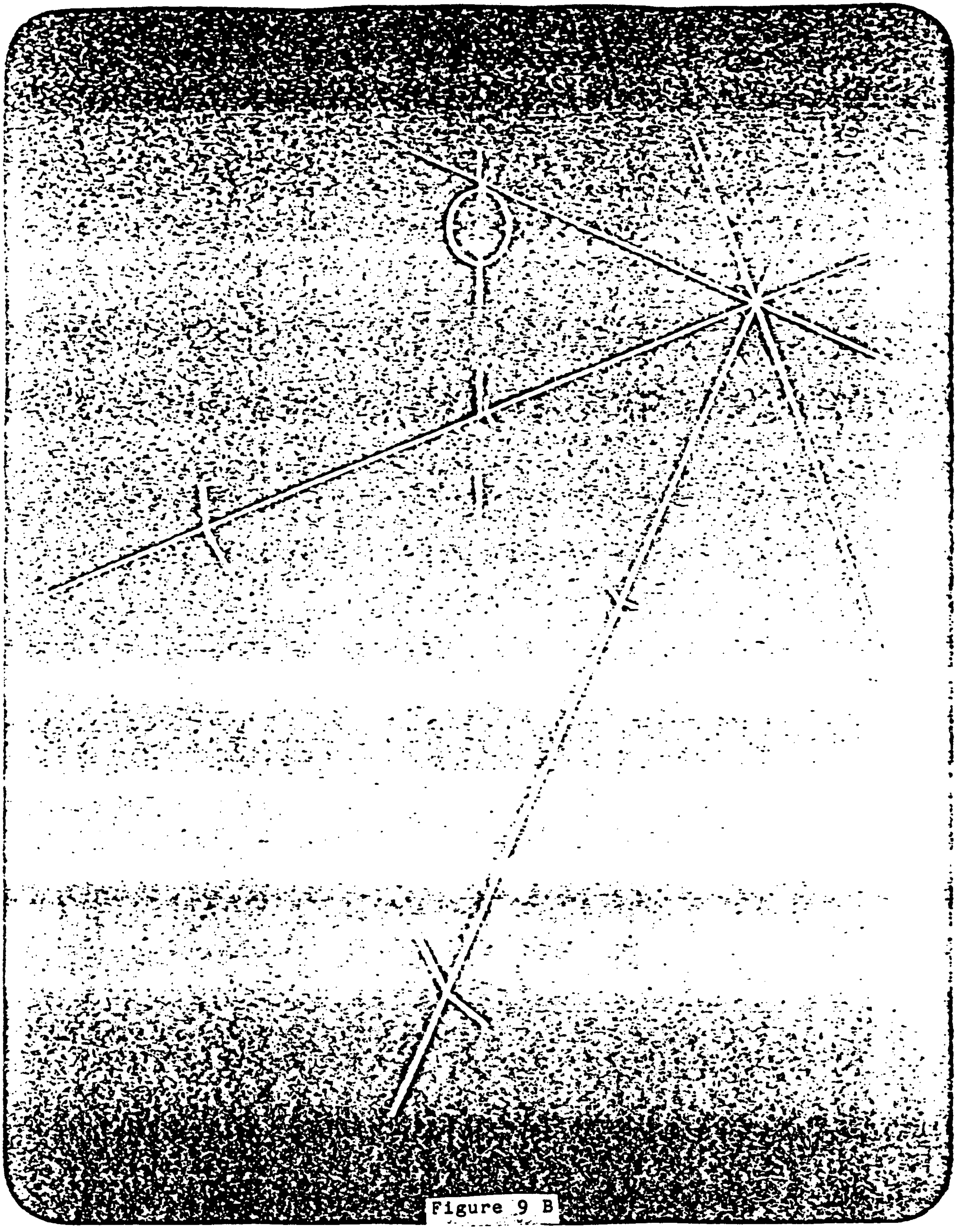
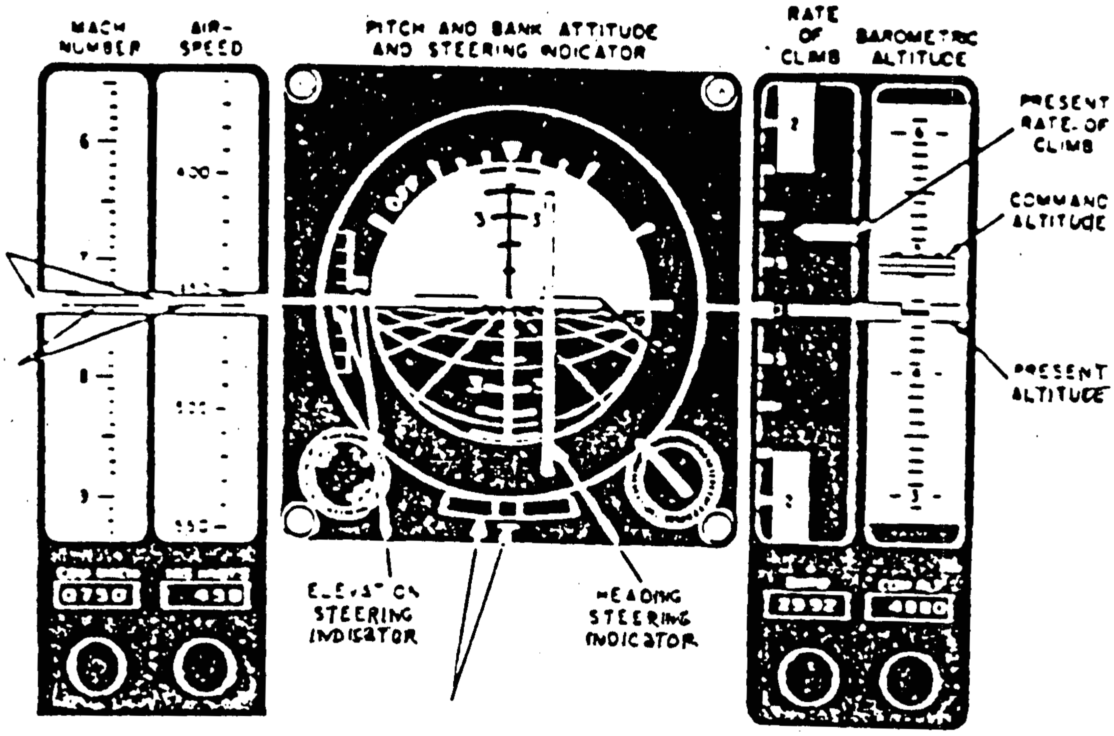


Figure 9 B



ADAPTED FROM AVIATION WEEK [illegible]
BY PERMISSION OF McGRAW-HILL PUB. [illegible]

Figure 13.6 USAF Integrated Cockpit Display, Showing Mock-up of Pitch-Bank Axis Portion ("Forward Look") (after Klass 13-15)

The "forward-looking" portion of the panel is planned to provide a single frame of reference in interpreting instrument indications by providing a common center line that extends across all instruments in the row (see Fig. 13.6). When the aircraft goes into a climb, for example, changes in all the rate and displacement indications (displayed side by side) are consistently related to the center reference line and to the pilot's control movement. Insofar as possible, scale displacements are in a single direction. Note also that actual performance data and desired performance values are displayed so that the pilot does not have to remember specific values. Instead, he flies the aircraft so as to keep the indices aligned across the reference line.

(Extract from "Vision in Military Aviation", Wolfeck, et al 1958. WADC-TR-399 p. 285)

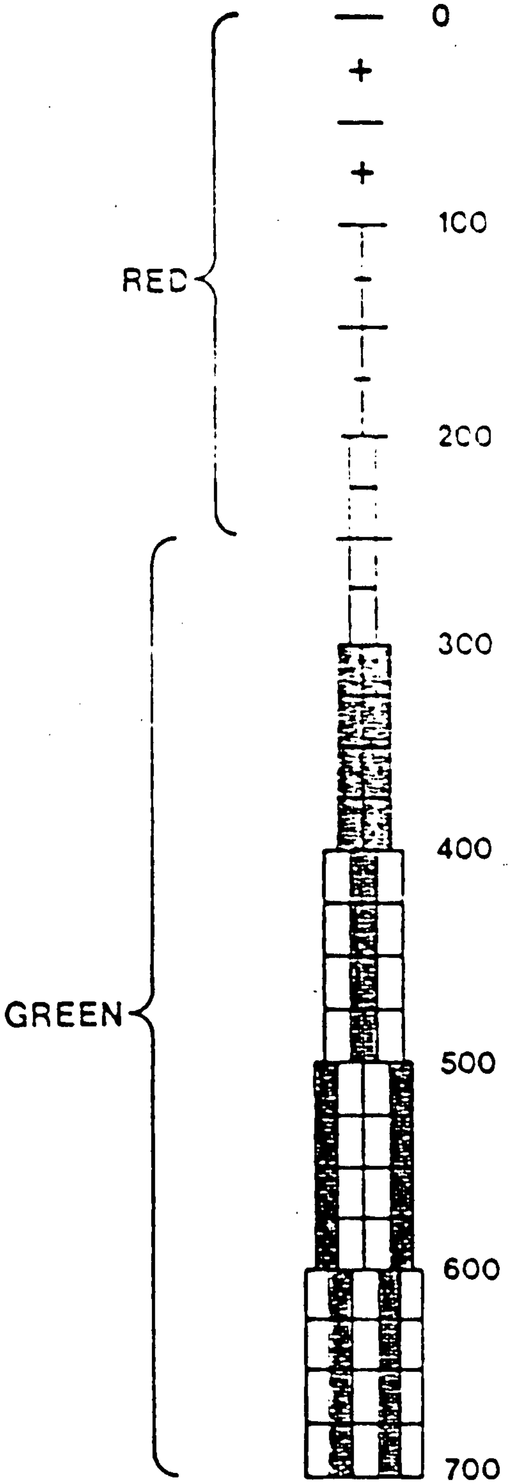


Figure 11

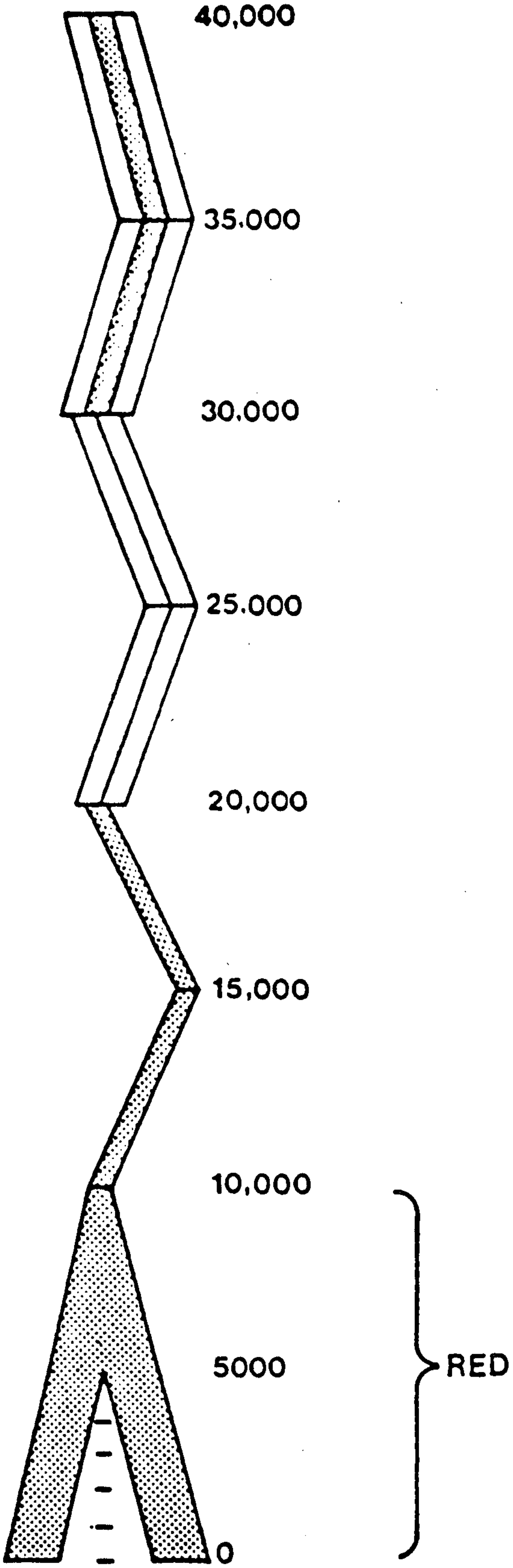


Figure 12

WELCOME TO AIRCRAFT ATTITUDE AWARENESS WORKSHOP

8 October 1986
by
Lieutenant General Thomas H. McMullen
Commander, Aeronautical Systems Division
Wright-Patterson Air Force Base, Ohio

BIOGRAPHY

Lieutenant General Thomas H. McMullen is Commander of Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

General McMullen was born July 4, 1929, in Dayton, Ohio, and graduated from Alamo Heights High School, San Antonio, Texas. He attended St Mary's University in San Antonio and graduated from the US Military Academy, West Point, NY, in 1951 with a bachelor of science degree in military engineering and a commission as a second lieutenant in the US Air Force. He received a master of science degree in astronautical engineering from the Air Force Institute of Technology, Wright-Patterson Air Force Base, in 1964; a master of science degree in administration from The George Washington University, Washington, DC, in 1971; and graduated from the Industrial College of the Armed Forces, Fort Lesley J. McNair, Washington, DC, in 1971.

After graduating from the academy, General McMullen entered pilot training at Hondo Air Base, Texas, and received his pilot wings at Bryan Air Force Base, Texas, in August 1952. He then completed fighter combat crew training at Nellis Air Force Base, Nevada. In December 1952 he was assigned to the 16th Fighter-Interceptor Squadron, 51st Fighter-Interceptor Wing at Suwon, South Korea. While in Korea he served as a flight commander and flew 78 combat missions in F-86's.

In November 1953 General McMullen went to Kelly Air Force Base, Texas, as a flight test maintenance officer. He test flew 30 types of aircraft after they had undergone depot maintenance. In 1959 he joined the General Dynamics Air Force Plant Representative Office in Fort Worth, Texas, and for the next three years was a B-58 flight test acceptance pilot.

He entered the Air Force Institute of Technology in September 1962 and two years later, following graduation, was assigned to the Space Systems Division at Los Angeles Air Force Station, Calif, as project officer in the Gemini Launch Vehicle System Program Office. He managed the effort for real-time monitoring of slow guidance malfunctions, abort situations and crew safety during boosted flight in the National Aeronautics and Space Administration's Gemini program.

The general went to the Republic of Vietnam in February 1967 as air liaison officer for the 25th Infantry Division at Cu Chi and flew more than 450 combat missions in O-1 Bird Dogs. In March 1968 General McMullen joined National Aeronautics and Space Administration headquarters, Washington, DC, as assistant mission director of the Apollo program. He assisted in coordinating the preparation of Apollo space vehicles for flight, and for training ground and flight crews for missions six through 13.

He graduated from the Industrial College of the Armed Forces in August 1971 and was assigned to the Aeronautical Systems Division at Wright-Patterson Air Force Base as deputy system program director of the B-1 development program. In June 1973 he was assigned as the system program director of the A-10 close air support aircraft. General McMullen managed the A-10 through the development and initial production phases.

General McMullen became vice commander of the US Air Force Tactical Air Warfare Center at Eglin Air Force Base, FL, in December 1974 and took command in September 1975. He served as deputy chief of staff for requirements, Tactical Air Command, Langley Air Force Base, VA, from October 1976 to March 1979. He then was appointed deputy chief of staff for systems, Air Force Systems Command, with headquarters at Andrews Air Force Base, MD. In July 1980 General McMullen returned to Langley Air Force Base as Tactical Air Command's vice commander. He assumed his present command in August 1982.

The general is a command pilot with more than 7,300 flying hours in 46 types of aircraft and wears the master missile badge. His military decorations and awards include the Distinguished Service Medal with one oak leak clusters, Silver Star, Legion of Merit, Distinguished Flying Cross with one oak leaf cluster, Bronze Star Medal, Meritorious Service Medal with one oak leaf cluster, Air Medal with 18 oak leaf clusters, Air Force Commendation Medal with one oak leaf cluster, Purple Heart, Presidential Unit Citation emblem, Air Force Outstanding Unit Award ribbon with "V" device and one oak leaf cluster, Air Force Organizational Excellence Award ribbon with one oak leaf cluster, Republic of Korea Presidential Unit Citation and Republic of Vietnam Gallantry Cross with palm. He also received the National Aeronautics and Space Administration Exceptional Service Medal and two Group Achievement Awards for the Apollo program. He is a life and hereditary member of the Order of Daedalians; an associate fellow of the American Institute of Aeronautics and Astronautics; a registered professional engineer in Ohio; and a member of Tau Beta Pi National Honor Society.

He was promoted to lieutenant general July 1, 1980, with same date of rank.

General McMullen is married to the former Clara Kirkwood. They have three children: Susan, Thomas and John. General McMullen is the son of Major General Clements McMullen, now deceased, an Air Force pioneer.

Good morning! I'm pleased to welcome you to Aeronautical Systems Division--the "Bicycle Shop." As some of you know, we take pride in the association we feel for the Wright Brothers--and to the great engineering work they did in starting aviation, right here, in their bicycle repair and sales shop on Third Street in Dayton. In fact, the development of military aviation has centered in the Dayton area since the Wright Brothers successful early flights over Huffman prairie, about a mile from here. It seems appropriate to hold an important meeting on aircraft attitude awareness here where flight was pioneered and where the future of Air Force aviation is taking shape today.

The topic of this workshop addresses one of the most critical areas of the pilot-vehicle interface (PVI). We have experienced events of pilot disorientation since the beginning of man's flight. All too often these events result in an accident that costs us a pilot as well as the aircraft. And our new aircraft--particularly our newest single-seat fighters--present some challenges that increase the tendency for pilot disorientation. We are preparing to take the next step in acquiring our next generation single-seat fighter, the Advanced Tactical Fighter. If we have a problem today in the PVI, we need to ensure that we undertake the efforts needed to address it, now.

Currently we're flying aircraft that perform better and are far safer than in the past--aircraft that malfunction and break less often than their predecessors. This hasn't come easy; we've devoted lots of effort to get where we are. And because we know we have lots yet to do, we're bunching our muscles to take further big steps on ATF. We need to make the same commitment on the pilot and his interface with the machine. We need help on how the pilot functions, how his brain works, how his visual and perceptual systems operate, and how he breaks down. We need help in understanding man as a critical systems component. We need that help to take advantage of the pilot's strong points while giving full consideration to his weaknesses as we work for the optimal interface design. This has important implications for the types of displays, whether visual or auditory, that most effectively convey the information he needs to maintain his orientation, and if he loses it, to help him quickly regain it. To help us resolve this critical problem, we've invited a number of experts in the human sciences fields here today to share their knowledge on how the pilot functions and what he needs for attitude awareness.

Fighter pilots face a challenging job. Because of that they go through a special selection process and then rigorous training. To be successful, they must be bright, quick to learn, adaptable, and competitive. It seems to me they're excellent copers; they take great pride in their ability to master the machine and can learn to make do with whatever they are given. There's even a certain amount of pride and prestige at being able to handle aircraft with less than optimal design features. Pilots can learn to work around even poorly designed features; eventually, though, there must be some cost involved, either in terms of operational or performance effectiveness, or of safety. Once they've learned to cope with some suboptimal design feature, it may no longer appear to them as a significant problem; they may fail to realize that it could be reducing their efficiency. They may even develop some resistance to change for improvement since they've learned to do it the hard way and their habit patterns are established. Fighter pilots love to fly; I've observed over lots of years that they tend to fall in love with whatever aircraft they happen to be currently flying, tending to minimize its undesirable features--although I think that's less now than formerly. But, for these reasons, they may not always be the most objective of evaluators--even though their inputs are essential. When they discuss problems about their aircraft, we need to listen.

The single-seat pilot has the most challenging mission. He must do it all himself. He has no one to help him with his job of aviating, communicating, navigating, and attack; no one to catch his oversights or errors and no one to help him cope with in-flight problems or emergencies. No question he has fewer of those long boring hours and that more of his time is intensely exciting, busy and disorienting--or even frightening--though he might not admit it.

He may fly when he is tired; surely that'll be his lot in combat. He commonly flies at night when being tired is a given. And when he's flying tired or at night or in the weather, he's more subject to illusions and disorientation--the classic pilot's vertigo.

There's another form of spatial disorientation to which he is subject and which I believe warrants our attention; that is, unrecognized disorientation or "misorientation," an insidious and lethal form because it does not alert the pilot that anything is wrong. It is this subtle form of spatial disorientation that is being seen more frequently now in our single-seat fighters.

Now a word about these single-seat fighters. These aircraft share certain features such as head-up-displays (HUDs) which provide a less-than-optimum attitude reference; wide area bubble shaped canopies that gather glare and reflections; often a cockpit lighting system that is a tradeoff to meet conflicting demands, and flight control systems which provide him less feedback than he's historically gotten. Over the years we've emphasized the daytime air superiority role, trading down features that might make the aircraft better at night or in weather. When flown in such conditions, the aircraft may deceive the pilot or fail to provide him the information he needs in a form he can quickly grasp.

I believe we have here, today, the necessary ingredients to shed some light on this challenge. We have a group of fighter pilots who will discuss their problems in their particular aircraft. After listening to their stories and evaluating their aircraft, we need to address some critical questions:

- Is there something about the design of these aircraft that tends to lead to loss of attitude awareness?
- If so, are there any reasonable fixes to improve attitude awareness in these aircraft in which the benefits outweigh the cost?
- And finally, what can we do to optimize man and machine integration and ensure we do not repeat past mistakes in future aircraft?

These are the basic questions to which I hope we find some answers during the next few days. The goals of this workshop are really twofold: First, to emphasize to our avionics and airframe people the pressing need for better aircraft attitude awareness in our single-seat fighters, and second, to turn loose the creativity/imagination that exists in this group to help us to progress in solving this very real problem.

At a meeting like this, some of the best work occurs during the breaks or the informal get-togethers. We hope you'll attend the get-together tonight at the Fly-Wright and tomorrow night for supper at the Defense Electronics Supply Center Officers Club. We also invite you to visit the Air Force Museum which we're certain you'll find worthwhile.

EDITOR'S NOTE

General McMullen added that ATF Requests for Proposal had been released this week, and that future aircraft designers must place much greater emphasis upon the pilot, stating that the pilot needs a better cockpit.

LOSS OF AIRCRAFT ATTITUDE AWARENESS:
IMPACT ON THE USAF
NEW TECHNOLOGY - OLD PROBLEMS

Brig. General Albert L. Pruden, Jr.

BIOGRAPHY

Brigadier General Albert L. Pruden Jr. is director of aerospace safety, Headquarters Air Force Inspection and Safety Center, Norton Air Force Base, Calif.

General Pruden was born Feb. 14, 1934, in Rolesville, N.C. He graduated from North Carolina State University with a bachelor of science degree in aeronautical engineering and was commissioned a second lieutenant in the U.S. Air Force through the Reserve Officer Training Corps program in 1955. The general received a master of arts degree in business management from New Mexico Highlands University in 1977. He is a graduate of Air Command and Staff College at Maxwell Air Force Base, Ala., in 1966 and Industrial College of the Armed Forces in 1973.

Beginning his career with pilot training at Kinston Air Base, N.C., and Greenville Air Force Base, Miss., General Pruden received his wings and was assigned to Perrin Air Force Base, Texas, for F-86D interceptor training in May 1956. He joined the Air Defense Command in April 1957 and was assigned to the 317th Fighter-Interceptor Squadron, McChord Air Force Base, Wash., flying F-102 Delta Daggers. He later moved with the squadron to Elmendorf Air Force Base, Alaska. In April 1959 General Pruden joined the 71st Fighter-Interceptor Squadron, Selfridge Air Force Base, Mich., and began flying F-106 Delta Darts. During this assignment he completed Instrument Pilot Instructor School and Interceptor Weapons School.

From September 1962 to August 1965, he served as an F-106 instructor pilot and weapons systems instructor at Tyndall Air Force Base, Fla. While there General Pruden assisted in forming the Combat Crew Training Squadron, was selected to conduct high-altitude tests in F-106s and began efforts which led to the 20mm cannon being added to the F-106 armament system.

Following graduation from Air Command and Staff College in July 1966 and F-4 transition training at MacDill Air Force Base, Fla., General Pruden was assigned to the 366th Tactical Fighter Wing "Gunfighters" at Da Nang Air Base, Republic of Vietnam, from December 1966 to August 1967. While in Southeast Asia, he flew 140 combat missions in F-4C's, including 100 missions over North Vietnam.

Upon his return to the United States, he was assigned to the F-4 System Program Office at Wright-Patterson Air Force Base, Ohio. He later served as deputy director of the F-4E Operational Test and Evaluation Program and led development of the modified cockpit switchology incorporated in present-day F-4E's. He was also actively involved in developing and testing the Target Identification System Electro-Optical and leading edge slats for the aircraft.

In July 1970 he became a member of the Joint Strategic Integrated Planning Staff, Organization of the Joint Chiefs of Staff, Washington, D.C. General Pruden returned for a second tour of duty in Southeast Asia in February 1973. He was assigned to the 8th Tactical Fighter Wing, Ubon Royal Thai Air Force Base, Thailand, as operations officer for the 433rd Tactical Fighter Squadron and later commanded the 25th Tactical Fighter Squadron. At the end of the Vietnam conflict, he had flown 233 combat sorties in F-4C's, D's and E's.

He returned to the United States in 1974 and served at the Air Force Test and Evaluation Center, Kirtland Air Force Base, N.M., where he managed the F-15 operational test and evaluation and was chief of the Fighter Branch.

Moving in April 1977 to the 32nd Tactical Fighter Squadron, Camp New Amsterdam, Netherlands, General Pruden served initially as vice commander. He assumed command of the squadron in January 1978 and led the unit's transition from F-4E's to F-15s. The squadron was later awarded the Air Force Outstanding Unit Award and the Hughes Trophy for this period. On departing that assignment in November 1979, General Pruden was awarded the Commandeur de Orde van Oranje-Nassau, met de Zwaarden (Commander in the Order of Orange-Nassau, with Swords) by the Queen of the Netherlands.

From November 1979 to May 1980, General Pruden was vice commander of the 50th Tactical Fighter Wing, Hahn Air Base, Germany. He took command of the 26th Tactical Reconnaissance Wing at Zweibrucken Air Base, Germany, in May 1980. Under his command the wing integrated improved production and prototype all-weather, near real time reconnaissance systems into its operational mission. In February 1982 General Pruden became the director of inspection at the Air Force Inspection and Safety Center. He assumed his present duties in July 1984.

The general is a command pilot with more than 4,800 flying hours in fighter aircraft. He has flown F-86D's; F-102s; F-106s; F-4C's, D's and E's; RF-4C's; F-15s; and F-16s. His military decorations and awards include the Legion of Merit with one oak leaf cluster, Distinguished Flying Cross, Meritorious Service Medal with one oak leaf cluster, Air Medal with 16 oak leaf clusters and Joint Service Commendation Medal.

He was promoted to brigadier general Sept. 1, 1982, with same date of rank.

General Pruden is married to the former Constance Bijold of Duluth, Minn. They have three children: Robert, Adele and Mary. His hometown is Rolesville, N.C.

INTRODUCTION

In 1984, 20 of 41 operator-factor accident reviews cited "loss of situational awareness" as a probable contributory factor.

- 5 of these were inadvertent flight into the terrain (spatial disorientation/misorientation).
- Other factors commonly noted were task saturation, distraction, and channelized attention.
- This group had a high fatality rate due to ejection out of the envelope or no ejection attempts.
- In 1985, similar patterns.

THE IMPACT OF AWARENESS ON TWO OF OUR HUMAN FACTOR PROBLEMS IN NEWER AIRCRAFT

To date, inadvertent flight into the terrain and G-induced loss of consciousness (GLC) appear to have contributed to half of F-16 operator-factor mishaps.

- Spatial Disorientation (SDO) is an old problem that is very much still with us.
  - Loss of feedback through stick, rudder, throttle, visual and auditory channels; (a good sportscar is good because of "road feel").
  - Overconfidence or "euphoria" is subtle. (Magic visibility and smmmoooothness).
  - Less than ideal cockpit for instrument flight.
- GLC represents a recently recognized threat and is an example of good results of increased awareness.
  - G onset rate may be more rapid in fly-by-wire.
  - Confidence in the G-limiter contributes to abrupt pulling.
  - Body position basic to effective straining.
  - Period of incapacitation (>12-15 seconds).

GLC prevention measures stress pilot awareness and are in progress, including centrifuge training.

-- Mental and physical preparation, early and effective straining, body position (especially checking 6), adequate duration.

-- So far in 1985, only one GLC (4 in 1984).

Potential measures to counter the SDO threat include both training and design concerns.

- -- Training (not always preventive, but rather to enhance recognition and recovery proficiency).
  - -- We can increase emphasis on instrument training in UPT/RTU programs (SEL rewriting ATC chapter on SDO).
  - -- We are making improved training films on SDO.
  - -- We can more widely apply low altitude awareness training type approaches (teaches attention management).
  - -- We have the VERTIFUGE, but can we design a trainer adequate to simulate <u>unrecognized</u> SDO?
- -- Cockpit Design concerns include flight instruments, warning systems, and distractions.
  - --- Flight instrument options.
    1. Reduce the number of digital displays.
    2. Improve information display on the HUD.
    3. Review basic efficiency of information transfer through flight instruments. (Instr. Flight Center)
  - -- Reduce cockpit distractions.
    1. Continue to pursue traditional control/switch position, and glare/reflection issues.
    2. Exploit automatic processing of orientational cues such as peripheral vision or auditory.

  As we proceed, let's be more aware of cues robbed from the pilot ... and if he still fails;

- -- Warning system options.
  1. GPWS.
  2. Can we build a system for automatic recovery?

CONCLUSION

Teamwork, the integration of multiple brands of expertise will move us ahead on the awareness issue more efficiently.

- -- Starts for safety with the whole mishap board asking the right questions.
- -- Regular, recurrent human factors working groups between appropriate USAF agencies have begun.
- -- Continue focused working groups such as this one as specific needs become apparent.
- -- We must continue the study of human information processing and its limits.

We will progress. We've seen some on GLC and are moving on SDO. We will make some on situational awareness. We will find out where to best invest our resources to prevent mishaps. New technology has given us fine equipment. We can bring a helpful perspective to that activity, a new technology of our own. Let's pull ahead together.

Editor's Note

Brig. Gen Pruden also included the following in his remarks:

- o The trend in spatial disorientation/misorientation mishaps is increasing - hope the F-16 C/D will be better.
- o SDO situations: might aerial refueling or refueling in the weather. Night low level formation approaches: wingman's problems when lead's formation lights do not work.
- o Fighting in clear blue sky - SDO has happened more than once to experienced F-15 pilots.
- o HUD dependence - canted cloud-deck viewed through HUD creates a mismatch.

- Recent F-16 RTU graduate hit an ILS stanchion making a night approach out of low overcast. His UPT was at Williams AFB (Arizona) where his instrument flying was all in simulators; LIFT was ACBT only with no instrument training; RTU was learning to deliver ordinance, no instrument training. Now at his operational base, he is making his first actual night weather approach, ever. We need to improve that.

- ATF should be a great leap forward in Aircraft Attitude Awareness, taking advantage of past mishaps history and all the new technology in displays and the Pilot Vehicle Interface. There's lots of new technology and we're in a position to make it happen.

- We need to test our systems using <u>new</u> as well as old fighter pilots.

Those flying frequently in actual weather conditions tend to go heads down in weather whereas those who fly less frequently in actual weather tend not to go heads down. But, the real issue is not whether heads up is better than heads down or vice versa.

We need to maximize the technology available to us today to make something that is better than either the HUD or instruments - or maybe a combination of the two.

THE ROLE OF VISION IN SPATIAL DISORIENTATION AND LOSS OF AIRCRAFT ATTITUDE AWARENESS BY DESIGN

by

Grant B. McNaughton, Colonel, USAF (MC) CFS
Chief Aeromedical Advisor, Life Support System Program Office
Deputy for Aeronautical Equipment, Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

BIOGRAPHY

Colonel Grant B. McNaughton is the Chief Aeromedical Advisor to the Life Support SPO, Aeronautical Systems Division, Wright-Patterson AFB, OH.

Colonel McNaughton was born 5 December 1934 in San Antonio, Texas. He graduated from Pomoma College and UCLA Medical School, interning at Boston City Hospital. Entering the Air Force in 1961, he became a flight surgeon and served tours in Illinois, Florida, Washington, North Dakota, Texas, and California. During the Southeast Asian conflict, he served with Air Commandos in Thailand and ran a 140-bed hospital in Laos. After some training in orthopedic and general surgery, he completed the Residency in Aerospace Medicine at Brooks AFB TX in 1975. He then served as Chief of Aerospace Medicine, Edwards AFB CA until 1980. Following this, he served as Chief of the Life Sciences Division at the Air Force Inspection and Safety Center, Norton AFB CA, where his analysis of numerous aircraft mishaps kindled his interest in aircraft attitude awareness. During his career as a flight surgeon, Col McNaughton investigated about 20 aircraft mishaps and consulted on countless others. While at the Safety Center, he wrote numerous articles on flying safety topics, including spatial disorientation, and helped make several movies on that subject.

Col McNaughton has over 2000 military flying hours in various aircraft, including the T-33, T-34, T-37, T-38, A-4, A-7, F-4, F-5, F-15, F-16, F-100, F-104, F-111, B-52, C-47, C-123, C-130, KC-135, C-141, and several helicopters. He is also a master parachutist. As a civilian pilot with about 1500 hours, he holds commercial, multi-engine, instrument and rotary-wing ratings. He has an abiding interest in aviation and has owned several aircraft in the past, including a Cessna-310, Starduster Too, Beechcraft Bonanza, and Cessna-185.

Col McNaughton is married to the former Jean C. Frost of Scranton, PA. They have four sons.

FIGURES

There are several topics and points I'd like to discuss in this briefing: the role of vision in spatial disorientation (SDO); design features that impact attitude awareness; importance of the attitude indicator; the fact that the HUD is not an ADI, although it could be improved as an attitude reference; and pattern-type displays that take advantage of the fact that the human is basically a pattern recognizer. We'll first talk about spatial disorientation (SDO) and how the man-machine interface and other inputs can lead to a loss of attitude awareness in some of our state-of-the-art fighters. Though Dr. Leibowitz will discuss the two modes of visual processing in more detail this afternoon, I need to explain something about it to provide some relevant background for this talk.

Historically, we've considered SDO to result from a mismatch between vision and the balance organ. We now know that is only part of the story. Just as important is a mismatch within the visual system itself, between its two modes of processing visual information. One of these modes is the all familiar focal mode which focuses, reads the checklist, identifies the bogey, and aims the gun. This mode is highly discriminating and is exclusively visual, in fact, is limited to the central 1-2° of the retina. It requires good lighting and good resolution, and it typically involves conscious attention.

The other is called the ambient mode because it orients oneself to the ambient environment. To demonstrate to yourself the orienting capability of the ambient mode, just try this little test popularized by Dr. Malcolm.

- Place your feet in a tandem (heel-toe) position, close one eye, cover the open eye with your fist through which you've made an aperture sufficient to maintain central or focal (or foveal) vision while blocking inputs from the periphery, and determine how long you can maintain your balance.
- Now try the converse of that test by clenching the fist to block focal vision but move your fist an inch or so away from your open eye so as to permit peripheral inputs. You should find you can hold your balance considerably longer, if not indefinitely, because your orientation inputs are going straight from your primary orientation sensor to the core of your balance centers.

This mode is concerned not with object recognition but with object quality, or more correctly, the quality of the surrounds; for example, the "surfaceness" of the surface, "horizoness" of the horizon, or "cockpitness" of an aircraft. It is a quality assessment mode, undiscriminating and uncritical, and it can be easily deceived, which, of course, is part of the problem.

Although this mode involves the entire retina, including central vision, it is by no means exclusively visual. It connects to the same terminals which receive orientation inputs from our organs of balance, proprioception and hearing. Instead of an ambient visual system, we have, in effect, an ambient orientation system, into which vision contributes its share of the inputs along with those from the other senses. When ambulating about on the surface with our eyes open, vision contributes the greatest proportion of orientation inputs, perhaps 90% or more; and of those inputs, the ambient mode provides perhaps 90%, so it supplies the lion's share. If we can see, or think that we can see, vision will dominate as far as orientation inputs are concerned. This mode works at any lighting level[2]: it's the one we use in the dark. Though you cannot read in a dark room, you can orient provided there is a minimum of light (Figure 1).

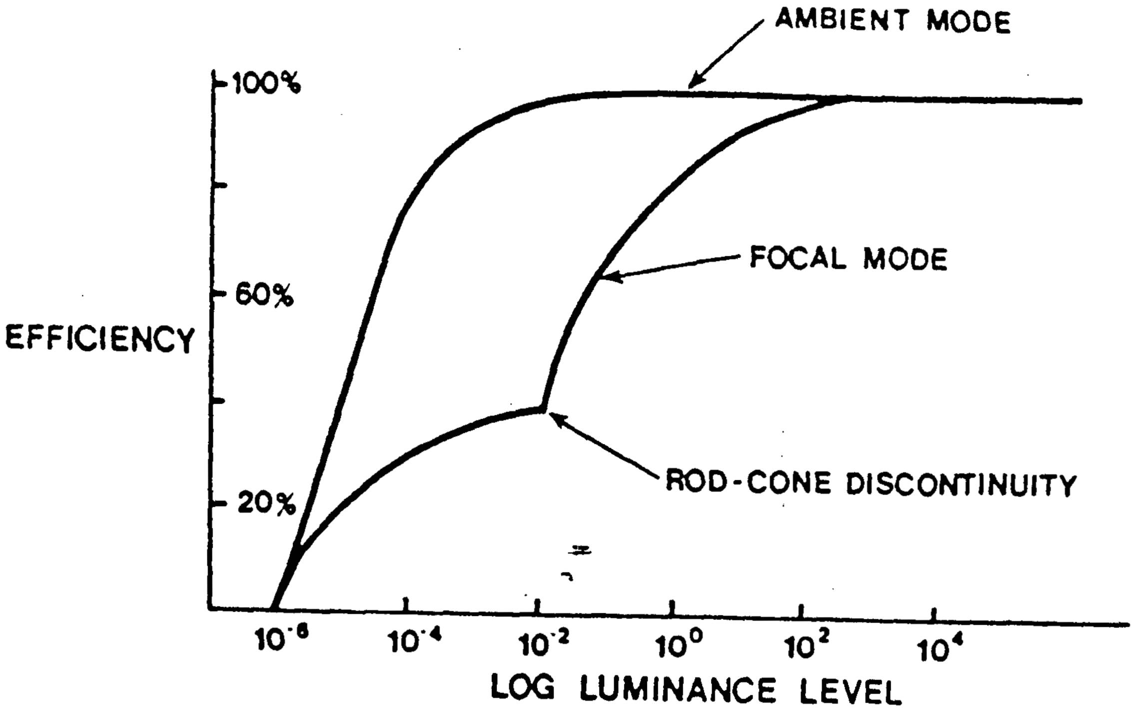


Figure 1: Focal vs. Ambient Visual Mode Efficiency - Effect of Decreasing Illumination.

Resolution is totally unimportant (Figure 2). You can orient with 20 diopter lenses before your eyes. The ambient mode typically functions at more of a reflex level. Along the scale of evolution, it's the mode that appeared first.[2]

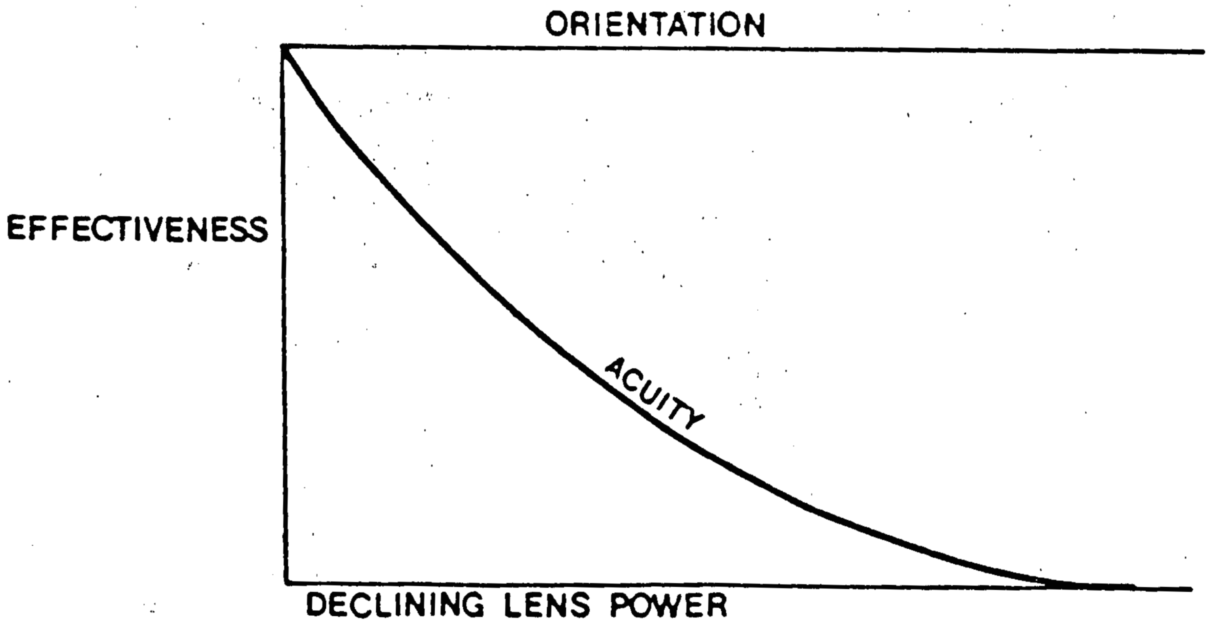
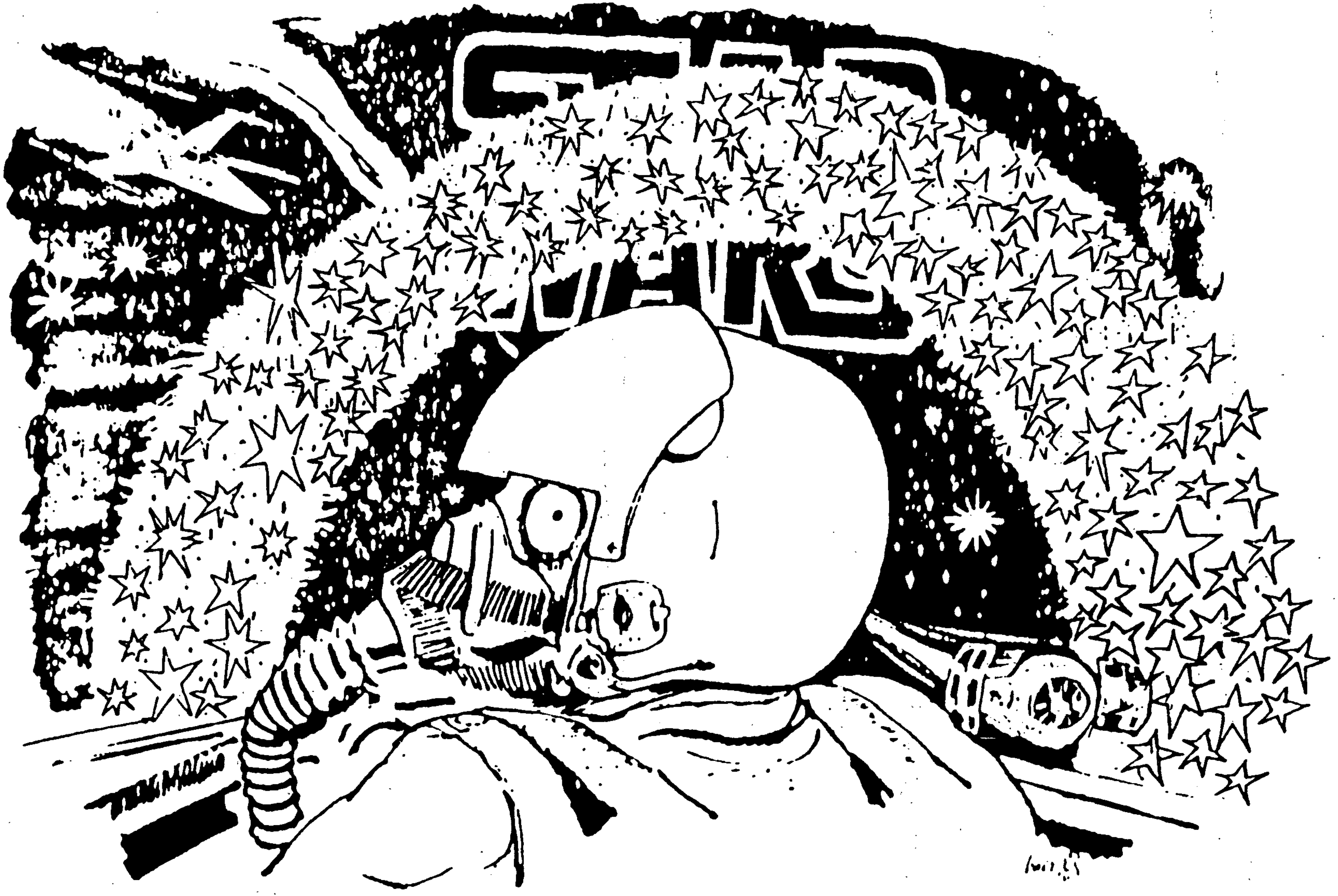


Figure 2: Focal vs. Ambient Visual Mode - Effect of Decreasing Resolution.

There are three consequences of ambient mode reactions of concern to pilots: the distraction potential, the vection illusion, and the tendency to orient to false horizons.

First, the brain contains receptors that are specifically tuned to the components of motion, both velocity and direction. An object whose motion is detected by the eye will trigger a neuron or clump of neurons to fire. If the velocity changes, it will fire a different neuron or clump, and if the direction changes, still a different neuron or clump. There is thus an architectural basis for responsiveness to perceived motion.[1] And after all, pilots are cocked to spot bogeys and avoid midair collisions and will likely snap glance to any movement. If the snap glance results in a substantial enough head motion, that may tumble their gyros causing vertigo. Thus, any motion can distract, even the slewing motion of the pitch scales on the HUD.



THE VECTION ILLUSION

Figure 3: Vection Illusion

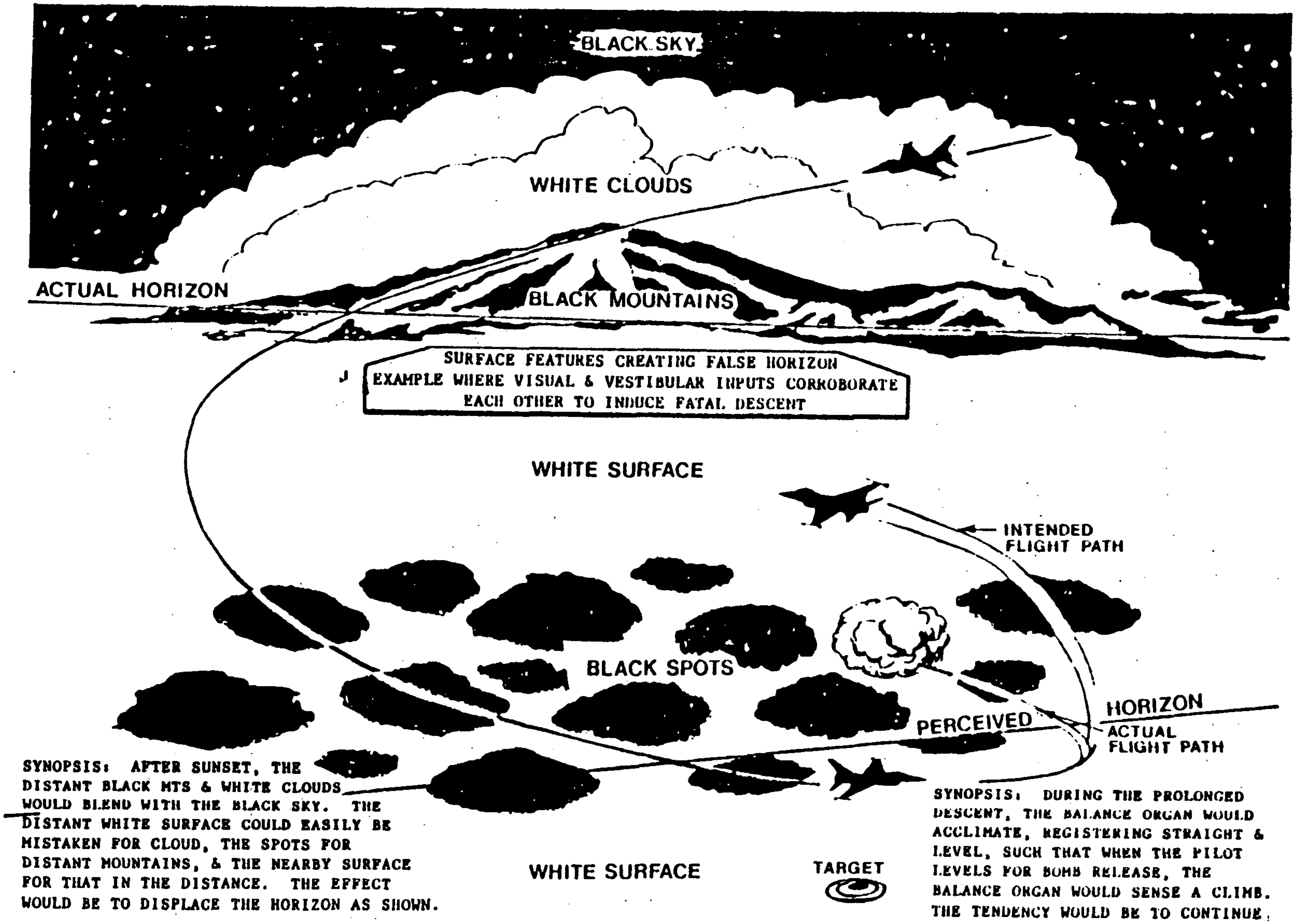
The same can apply to anything appearing out of place, such as bug spots on the windscreen; one experienced fighter pilot admitted to breaking for a bug spot, then breaking again within minutes for the same bug spot.

Whereas a small motion in the periphery may be interpreted as object motion, more of the periphery that moves will be interpreted as self-motion. You've all experienced this sensation while sitting at a stop light: as the car next to you begins to roll backwards, your impulse is to slam the brakes on your motionless car. This sensation is known as vection. It can be true or illusory, and it is the principle upon which full visual simulators are based. The sensation of motion created by these devices is sufficiently commanding that the motion bases are unnecessary and have commonly been deactivated.

Design features that potentiate distraction and disorientation include a wide area canopy, bubble-shaped like a "fishbowl"; a head position high up in this "fishbowl" subjecting the ambient mode to maximum bombardment with glare, reflections and false motions; light sources that cause glare and reflections off the canopy, that impede outside viewing, that impede the acquisition of a valid orienting phenomenon (horizon or surface), or that cause systematic motions such as described by A-10 pilots flying over a lighted runway at night. These reflections running from aft to forward up the canopy make it appear as though an airliner is passing overhead. They dub this the "Star Wars Effect" and admit that it's a real attention getter (Figure 3). Furthermore, the ambient mode is adequately activated by the low spatial frequencies, such as fuzzy shadows and reflections, typically stimulating large areas of the visual field.[2] The vection illusion can be exceptionally deceiving as well as disorienting.

Another finding of interest is the fact that the brain cortex subserving ambient vision contains receptors specifically responsive to lines and to edges. This has actually been mapped out in the brains of cats by Hubel and Weisel at Harvard, 1962,[3] and is probably true as well in humans. Since the human can't tolerate a sense of disorientation and since the ambient mode is uncritical, it will likely accept anything with the quality of "horizoness" as a valid horizon. There appears to be a sort of mass rule operating here: the larger, the more commanding. That may explain in part, at least, the commanding nature of phenomena such as sloping cloud decks, sloping terrain, a haze or fog-depressed horizon, the Northern Lights, or surface features resembling a horizon.

A particularly lethal combination is a night take-off across a lighted shoreline. Since the balance organ cannot distinguish between acceleration and a climb, as what appears to be the horizon passes beneath his wingline, the pilot becomes convinced he's doing a loop, and his tendency is to dump the nose and fly into the water.



SURFACE FEATURES CREATING FALSE HORIZON EXAMPLE WHERE VISUAL & VESTIBULAR INPUTS CORROBORATE EACH OTHER TO INDUCE FATAL DESCENT

SYNOPSIS: AFTER SUNSET, THE DISTANT BLACK MTS & WHITE CLOUDS WOULD BLEND WITH THE BLACK SKY. THE DISTANT WHITE SURFACE COULD EASILY BE MISTAKEN FOR CLOUD, THE SPOTS FOR DISTANT MOUNTAINS, & THE NEARBY SURFACE FOR THAT IN THE DISTANCE. THE EFFECT WOULD BE TO DISPLACE THE HORIZON AS SHOWN.

SYNOPSIS: DURING THE PROLONGED DESCENT, THE BALANCE ORGAN WOULD ACCLIMATE, REGISTERING STRAIGHT & LEVEL, SUCH THAT WHEN THE PILOT LEVELS FOR BOMB RELEASE, THE BALANCE ORGAN WOULD SENSE A CLIMB. THE TENDENCY WOULD BE TO CONTINUE THE DESCENT.

Figure 4: Misplaced Horizon on Night Bomb Drop

We think that surface features resembling a horizon have been responsible for a number of our mishaps. One involved an experienced fighter pilot flying an F-16 on a night bomb drop. The sun had just set, and from his orbit at 17,000 feet MSL, looking west, he could see in order, rapidly blackening sky, white clouds, black mountains, white terrain, black circular discontinuities through the white terrain, then more lighter terrain beneath him (Figure 4). As he descended toward bomb release ("pickle") altitude, he stabilized in his track sufficiently for his balance organ to register straight and level, such that when he levelled to pickle, his balance organ registered a climb. In want of better visual information, his tendency would be to continue the descent. Visually, while inbound to the target, he had the lights of a large city on the eastern horizon to enable orientation, but once he turned to downwind, he was confronted with a lightless, black hole. From his new viewpoint, the mountains and clouds both blended with the black sky, making the more distant white terrain appear as the cloud, the black discontinuities as the distant mountains, and the nearby light terrain as that in the distance. The effect was to displace the horizon downward 35-40°.

There were two additional factors impacting this pilot. One, the bomb failed to spot (i.e., it failed to flash) and troubleshooting a possible malfunction trapped his attention. And two, he was pickling that bomb at about his normal bedtime, so he probably wasn't as sharp as usual. These, coupled with the corroborating false vestibular and visual cues provided him the comfortable premise of a climb to downwind as intended, and he probably never bothered to cross-check his instruments.

With that background on the role of vision in SDO, let's discuss some problems with current fighter attack aircraft. I see them as:

- o Failing to provide adequate attitude references, both external references and instruments.
- o Failing to provide critical control parameters such as airspeed and altitude in a quickly digestible format.
- o Confusing, disorienting, and misorienting the pilot.
- o Providing inadequate tactile and/or auditory cues.

A number of human factors problems are exposed in the A-10 (Figure 5). First, the angled canopy rail denies the pilot a reference to the horizontal, and the stubby nose denies him a ready motion cue, either in the vertical or the lateral planes. Because this aircraft is so highly maneuverable, it is easy to inadvertently over bank it, in which case it will fly a descending flight path. If the pilot fails to catch that nose dropping through the

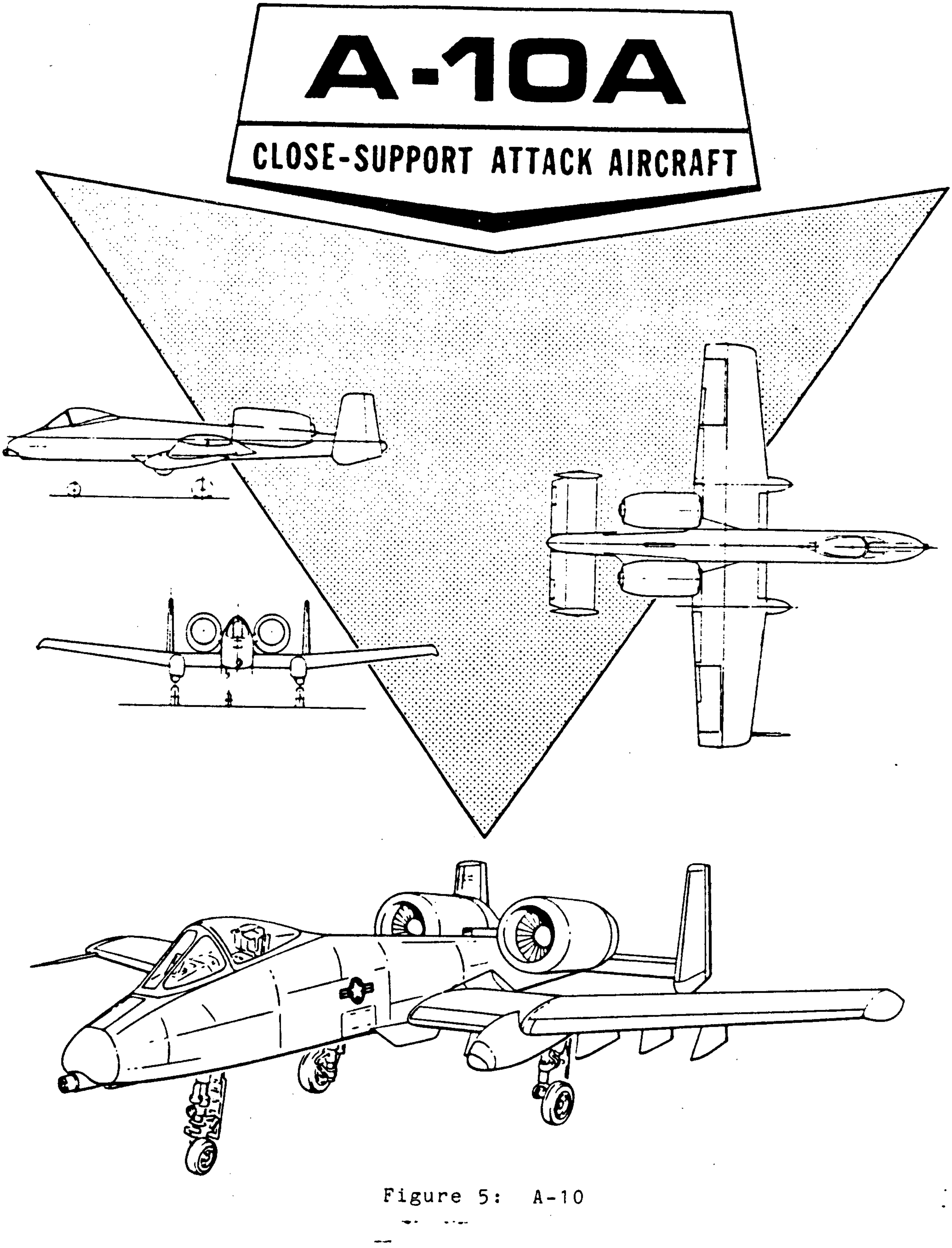


Figure 5: A-10

horizon early, he's committed to a dive recovery for which he may have insufficient altitude. That's important for this aircraft because of the low altitude where it operates. It also has no radar altimeter or ground proximity warning system.

From the cockpit (Figure 6), one can appreciate that the view out the front is cluttered: HUD supports, windscreen brace, and canopy bows can mask birds and aircraft. There are some potential attention traps: some of the avionics needed for flying in IMC, e.g., the radios, TACAN, and INS are located down on the side consoles, constituting potential head-down attentional/vertigo traps. Firing the Maverick Missile involves a multi-step procedure requiring the pilot to divide his attention between the stores management panel at lower left, the TV monitor at upper right for final slewing and lock-on, and the HUD to clear his flight path--a potential procedural, attentional and focus trap. The engine instruments are stacked left-right-left-right so that in the event of a mismatch, it's not always immediately apparent which engine's at fault.

The aircraft exhibits flight control characteristics which has created problems for pilots. Whereas most aircraft buffet before they stall, generating a reliable tactile cue that pilots ingrain and come to rely upon, the A-10 stalls before it buffets. We lost a number of them before breaking that code.

Another area where tactile cueing could stand improvement is the speed-brake. There is no cue, tactile or auditory, to remind the pilot that his speed brakes are deployed. Of course, he can see them if he thinks to look for them (split ailerons), but under pressure of an emergency, he may not think about them. This is important because, whereas the aircraft has a relatively ineffective propulsion system, it has a very effective speed brake, such that if an engine is retarded without retracting the speed-brake, the aircraft will not maintain altitude. We have lost several aircraft because the-pilot did just that; shut down an engine, failed to retract the speed brake, and was unable to figure out why he could not maintain altitude in sufficient time to avoid having to eject. In at least two of these instances, the pilots were in IMC, and just maintaining attitude while coping with the emergency absorbed all their attention.

The F-15 will be discussed in more detail by Major Merrill Beyer, but let me point out just two design features impacting attitude awareness:

First, the considerable amount of prime real estate taken up by the radio, transponder and HUD control panel (Figure 7). This has forced the location of the ADI, which is only 3" in diameter, down over 35° below the design eye line. It is not easy for the wingman to simultaneously fly formation and maintain his own attitude awareness. He must turn his head considerably to the side in order to fly good formation; the result can be an angular difference between the outside formation references and the line of

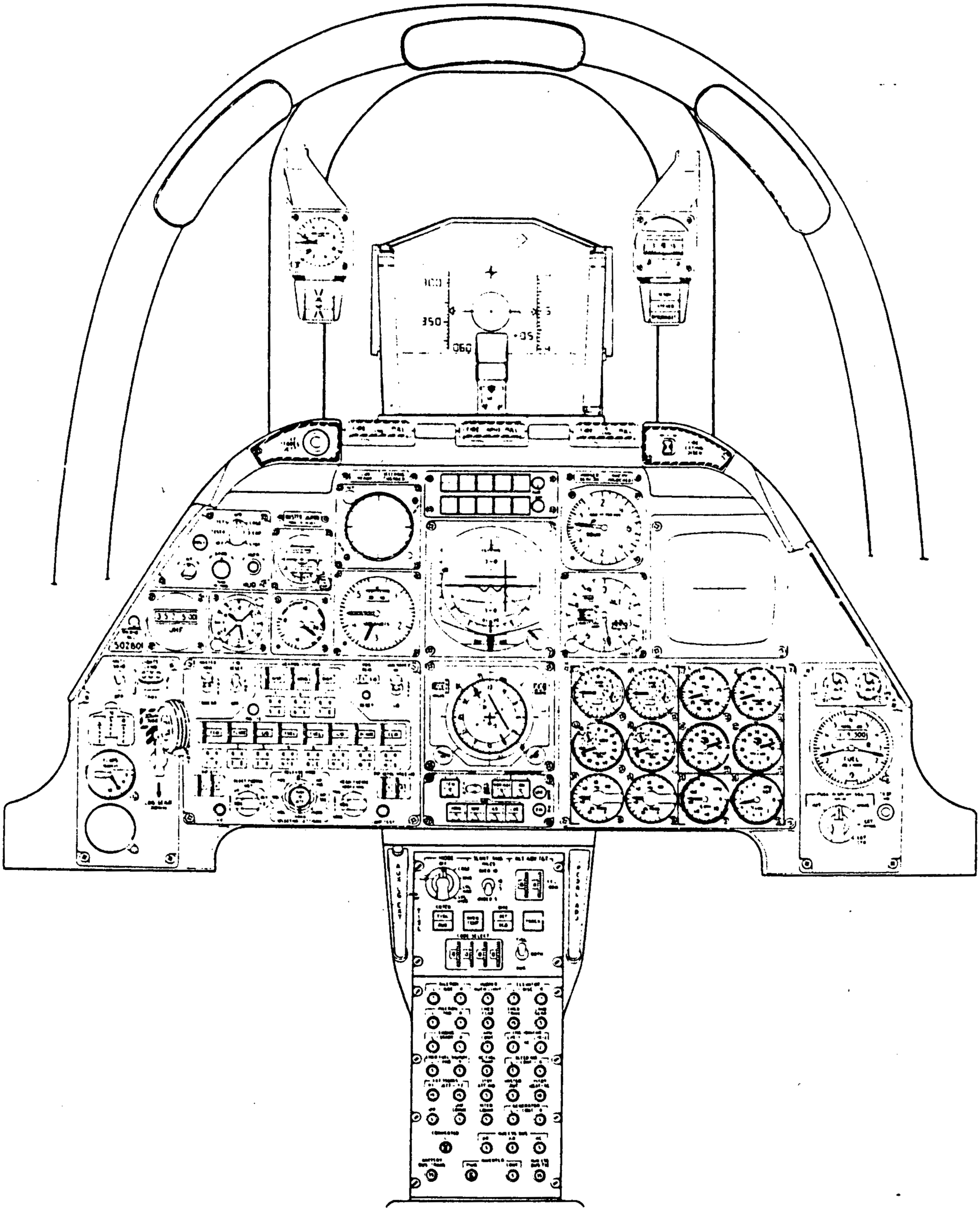
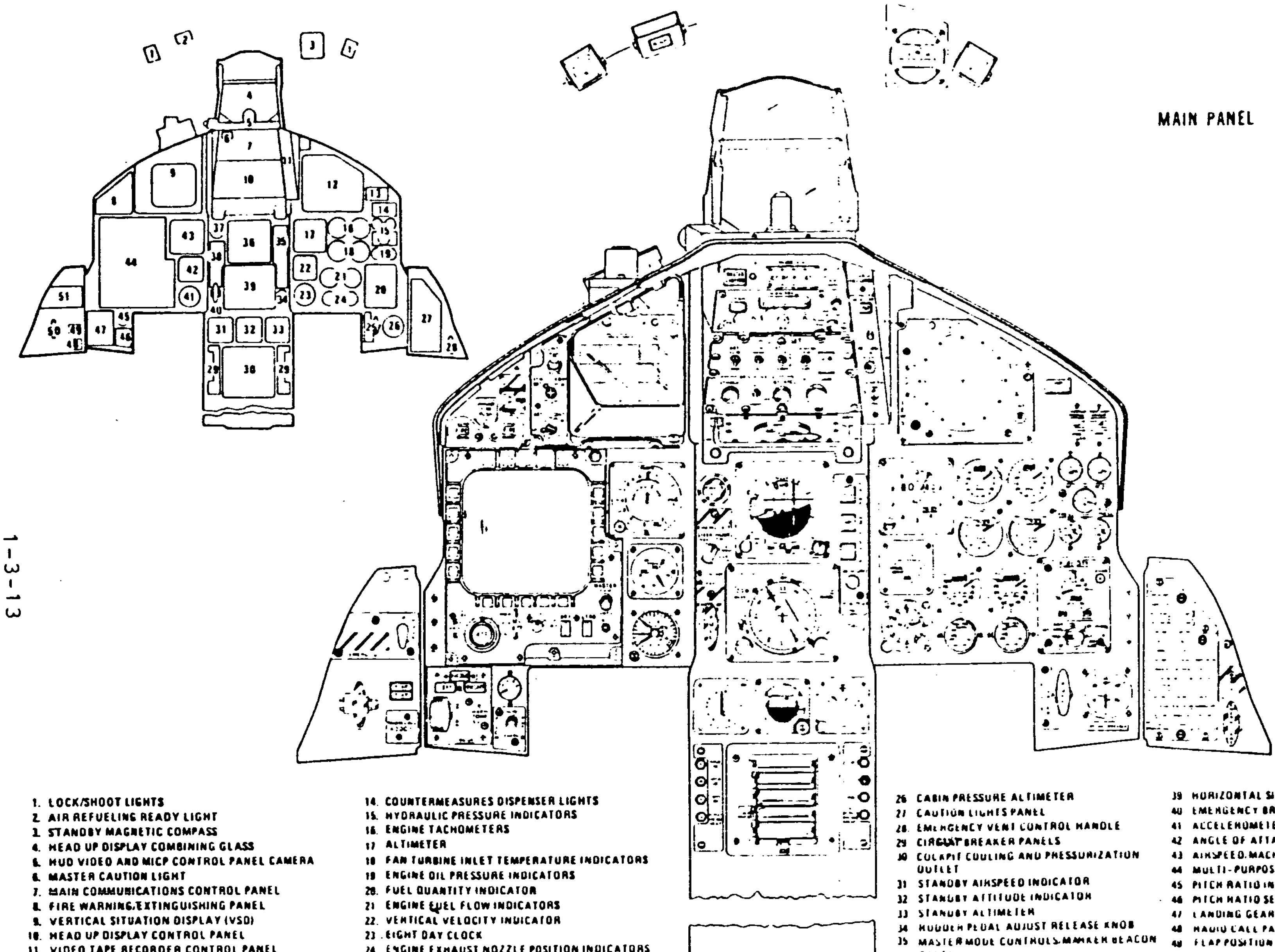


Figure 6: A-10 Instrument Panel



1. LOCK/SHOOT LIGHTS
2. AIR REFUELING READY LIGHT
3. STANDBY MAGNETIC COMPASS
4. HEAD UP DISPLAY COMBINING GLASS
5. HUD VIDEO AND MICP CONTROL PANEL CAMERA
6. MASTER CAUTION LIGHT
7. MAIN COMMUNICATIONS CONTROL PANEL
8. FIRE WARNING/EXTINGUISHING PANEL
9. VERTICAL SITUATION DISPLAY (VSD)
10. HEAD UP DISPLAY CONTROL PANEL
11. VIDEO TAPE RECORDER CONTROL PANEL
12. TEWS DISPLAY UNIT
13. CANOPY UNLOCKED WARNING LIGHT
14. COUNTERMEASURES DISPENSER LIGHTS
15. HYDRAULIC PRESSURE INDICATORS
16. ENGINE TACHOMETERS
17. ALTIMETER
18. FAN TURBINE INLET TEMPERATURE INDICATORS
19. ENGINE OIL PRESSURE INDICATORS
20. FUEL QUANTITY INDICATOR
21. ENGINE FUEL FLOW INDICATORS
22. VERTICAL VELOCITY INDICATOR
23. EIGHT DAY CLOCK
24. ENGINE EXHAUST NOZZLE POSITION INDICATORS
25. JET FUEL STARTER CONTROL HANDLE
26. CABIN PRESSURE ALTIMETER
27. CAUTION LIGHTS PANEL
28. EMERGENCY VENT CONTROL HANDLE
29. CIRCUIT BREAKER PANELS
30. COCKPIT COOLING AND PRESSURIZATION OUTLET
31. STANDBY AIRSPEED INDICATOR
32. STANDBY ATTITUDE INDICATOR
33. STANDBY ALTIMETER
34. RUDDER PEDAL ADJUST RELEASE KNOB
35. MASTER MODE CONTROLS/MARKER BEACON PANEL
36. ATTITUDE DIRECTOR INDICATOR
37. EMERGENCY JETTISON BUTTON
38. STEERING MODE PANEL
39. HORIZONTAL SITUATION INDICATOR
40. EMERGENCY BRAKE STEERING CONTROL HANDLE
41. ACCELEROMETER
42. ANGLE OF ATTACK INDICATOR
43. AIRSPEED/MACH INDICATOR
44. MULTI-PURPOSE COLOR DISPLAY (MPCD)
45. PITCH RATIO INDICATOR
46. PITCH RATIO SELECT SWITCH
47. LANDING GEAR CONTROL HANDLE
48. RADIO CALL PANEL
49. FLAP POSITION INDICATOR
50. EMERGENCY LANDING GEAR HANDLE
51. ARRESTING HOOK CONTROL SWITCH

Figure 7: F-15 Instrument Panel

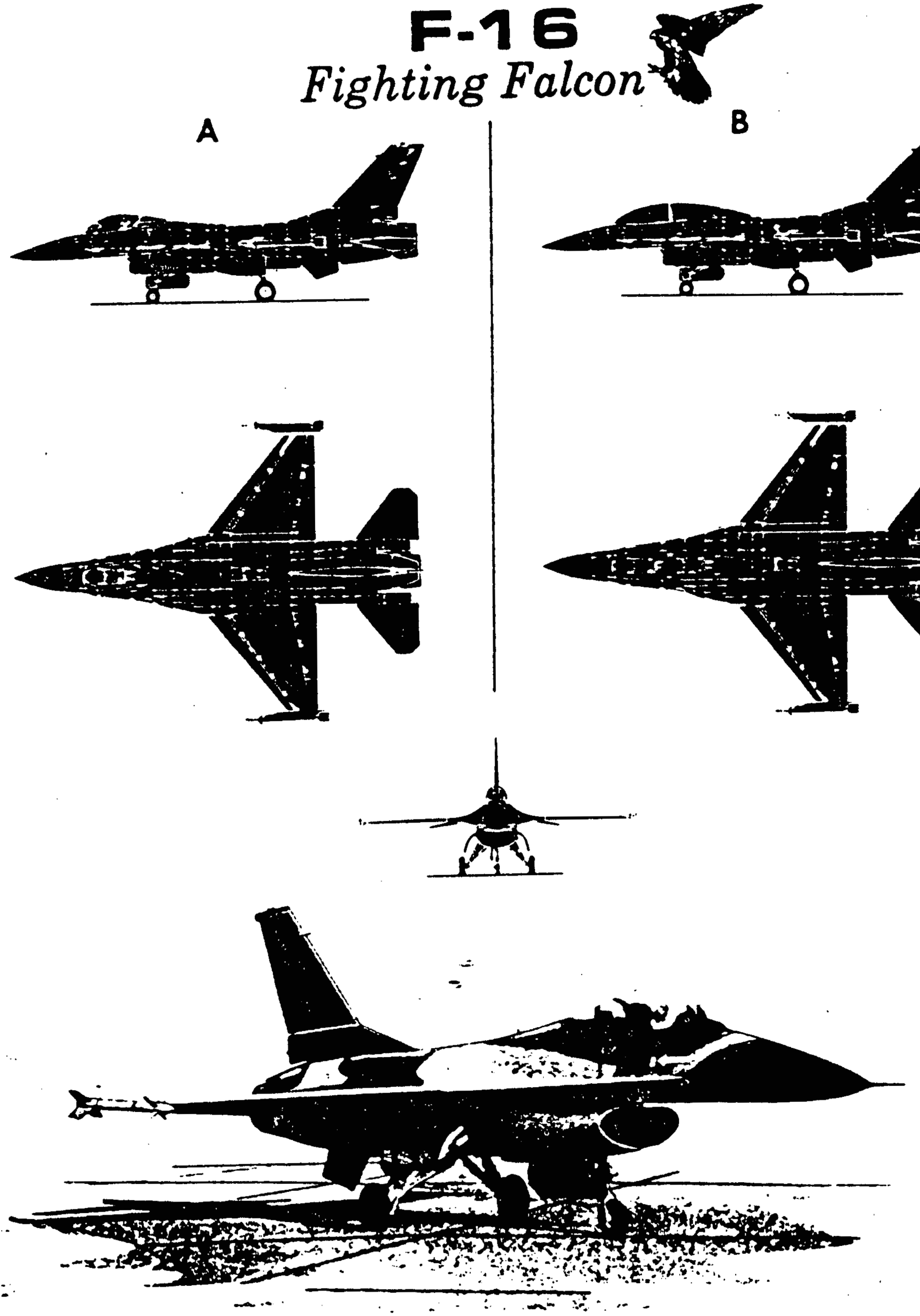


Figure 8: F-16 Planform

sight to his HUD or ADI by as much as 60°. This requires him to make significant head movements whenever he wishes to cross-check his cockpit instruments. Pilots know that large head movements in the cockpit can produce vertigo. In order to minimize these head movements, the wingmen prefer to slide down and back from the normal formation position. However, if the wingman drops too far down and in toward lead during intense weather formation flight, the wingman's aircraft wing overlaps the horizontal stabilizer of the lead aircraft. Not only is this somewhat dangerous, but it also can interfere with the normal flight dynamics of the lead aircraft to the extent that lead can "feel" when the wingman is in too tight. Pilots have also reported that they lose the F-15 when flying formation during day weather conditions more than any other tactical fighter they have flown. This is due to the gray paint scheme of the F-15 which minimizes color contrast with gray backgrounds, enabling the aircraft to easily blend into weather.[4]

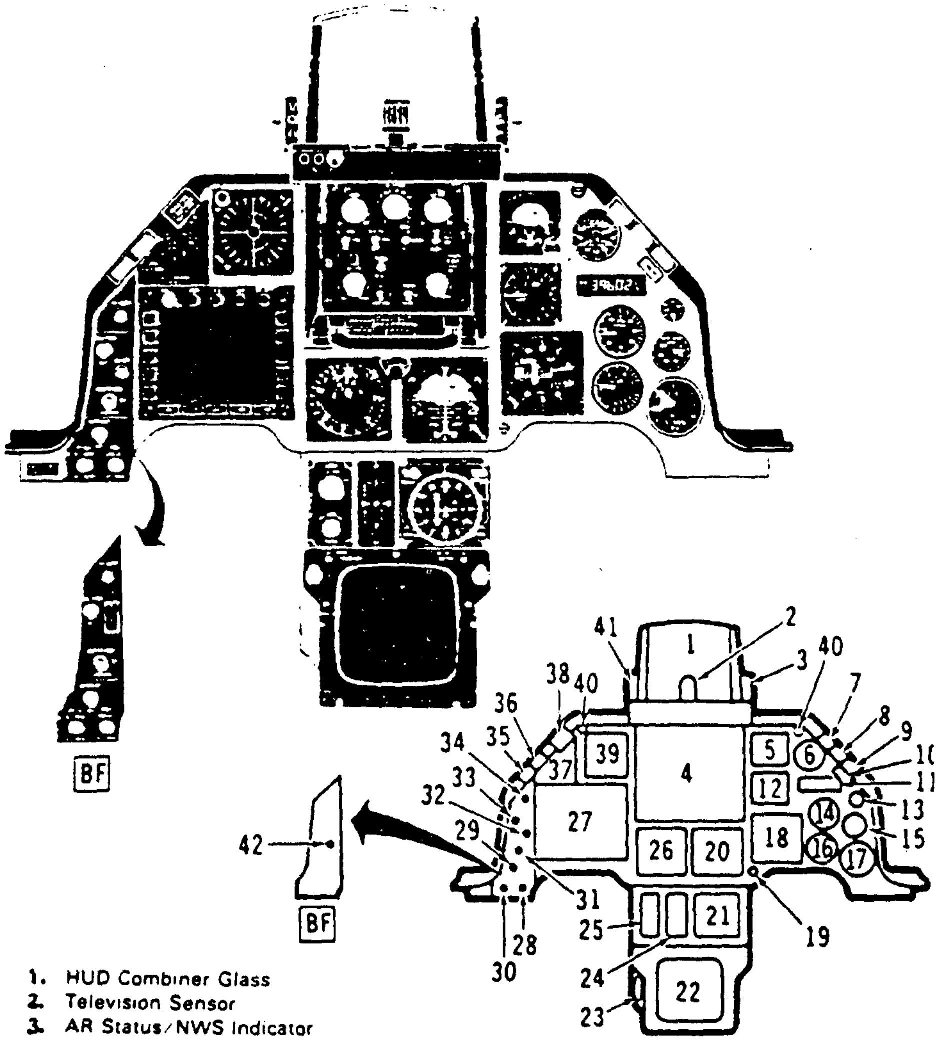
The other feature is the location of the Standby Attitude Indicator (SAI). It is deeper yet than the primary ADI, and it is behind the stick; it requires moving the stick (or leaning way forward) to view it.

The F-16 (Figure 8) was originally built as a day VFR lightweight fighter concept demonstrator, and as a day VFR dog-fighter, it is probably unparalleled. But it was not designed for the night-weather role, and when flown in such conditions, it generates its share of human factors problems (to be discussed later by Major Arthur Fowler), not the least of which are canopy glare and reflections from cockpit and instrument lights and from the radar scope. In addition, canopy reflections from clipboards, helmets, and other cockpit items occur about 30° forward of the pilot's ear line and prove distracting. Pilot's helmets were painted gray to decrease such reflections.

The F-16 aircraft lacks natural attitude references. From his seated position, the pilot may not be able to see much or any of the aircraft. The canopy bow is behind the pilot where some claim it blocks their view to the rear. Most pilots love the unsurpassed visibility, however, and would resist any change. Yet the pilot may get the feeling of being "on" the aircraft or suspended above it, like being on the nose of a dart or on a "magic carpet." That, coupled with the spectacular performance and lack of cues, has led to a feeling of unwarranted contentment or complacency, dubbed by a former F-16 Wing Commander, "F-16 Euphoria."[5] What impact it may have on one's time sense, cross-check, or situational awareness, if any, has not been formally studied, but we've had instances of inattention to critical parameters for excessive periods of time, resulting in thousands of feet of altitude loss and crashes.

This aircraft was built as a visual aircraft to keep the eyes out. It does not cue the pilot that anything has changed or that it's time to transition back inside, and when it is time to transition back inside, the aircraft presents a challenge. This begs the question as to what the pilot needs to transition back inside. If confronted with situations of false

INSTRUMENT PANEL A BF



1. HUD Combiner Glass
2. Television Sensor
3. AR Status/NWS Indicator
4. HUD Control Panel
5. Standby Attitude Indicator
6. Fuel Flow Indicator
7. DUAL FC FAIL Warning Light (Red)
8. HYD/OIL PRESS Warning Light (Red)
9. CANOPY Warning Light (Red)
10. ENGINE Warning Light (Red)
11. Radio Channel/Frequency Indicator
12. Vertical Velocity Indicator
13. Oil Pressure Indicator
14. RPM Indicator
15. Nozzle Position Indicator
16. FTIT Indicator
17. Fuel Quantity Indicator
18. Altimeter
19. MRK BCN Light
20. Attitude Director Indicator
21. Horizontal Situation Indicator
22. Radar/EO Display
23. Rudder PEDAL ADJ Knob
24. AOA Indicator
25. Instrument Mode Select Panel
26. Airspeed Mach Indicator
27. Stores Control Panel
28. Autopilot ROLL Switch
29. AUTOPILOT Switch
30. Autopilot PITCH Switch
31. MASTER ARM Switch
32. ALT REL Button
33. SMS PWR Switch
34. IFF IDENT Button
35. ENG FIRE Warning Light (Red)
36. T.O./LAND CONFIG Warning Light (Red)
37. THREAT WARNING Controls and Indicators
38. MASTER CAUTION Light (Amber)
39. THREAT WARNING Azimuth Indicator
40. Spotlight
41. AOA Indexer
42. BF OVRD Light

Figure 9: Instrument Panel
Block 10 Aircraft

motions, false horizons or no horizon; i.e., if he lacks God's big outside horizon, the pilot needs man's horizon, and the bigger the better. Whereas it may be permissible to miniaturize some instruments, miniaturization does not apply to the ADI. The ADI represents one instance where BIG is definitely BETTER, ideally big enough to see out the corner of the eye, as in flying formation.

But what in the way of an ADI does the F-16 provide (Figure 9)? Like the F-15, the large HUD control panel forces the primary ADI deeply into the cockpit, over 25° below the design eye line. Under certain lighting conditions, the top half may appear uniform, allowing the pilot to miss the fact that he's in a descent. The ADI is small; it's barrel is less than 2" in diameter, and depending upon how the seat is adjusted, could be anywhere from 25-33" from the eye, such that it fails to subtend a large angle or a large area at the eye; it is not particularly commanding. Finally, wide separation between the primary ADI and SAI precludes the immediate recognition of a mismatch between the two and upsets one's composite cross-check if required to switch. Although the SAI is less reliable than the primary ADI, its proximity to the eye line has resulted in its use to the exclusion of the primary ADI with disastrous results when it (the SAI) was in error.

I'd like to discuss a mishap illustrating the attitude instrument problem in this aircraft. The mission involved a day formation departure into a low overcast; the lead pilot was inexperienced, the wingman highly experienced, and as they departed, the wingman was on the right wing. Upon entering the overcast, the lead became disoriented, and after some gyrations, exited the clouds in a steep dive at a steep left bank. At this point, the wingman had moved to the left wing, so he was looking up at lead. As soon as they broke out, lead saw the trees, rolled and pulled hard, hitting some trees but getting the aircraft back. Wingman was just a millisecond too late.

This mishap illustrates two points. One, lead was unable to transition from outside to inside in a timely, positive manner; and two, despite his experience, the wingman could not simultaneously fly formation <u>and</u> maintain his own attitude awareness, because of the small size and deep location of the ADI.

Again, the importance of the attitude indicator: it's the hub of the cross-check. Studies have shown that pilots flying in IMC spend between 70-90% of their eye time dwelling on the ADI. It should be large, high, centrally located, and prominent enough to see out the corner of the eye: to facilitate the transition from outside to in; to enable the wingman to sneak-a-peek while flying formation; to facilitate maintaining one's own aircraft attitude awareness; to speed recognition of unusual attitudes, and to facilitate coping with unusual attitudes.

We haven't always had small ADI's, as illustrated by the instrument cluster developed at AFWAL by former Luftwaffe Colonel Siegfried Knemeyer

(Figure 10). At the hub of this cluster, which was near eye level in the F-105 and F-106 was an ADI, the sphere of which measured a full 3" in diameter. (The same integrated flight instruments are currently used in the F-111, C-5 and C-141, and were also used in the B-70.)

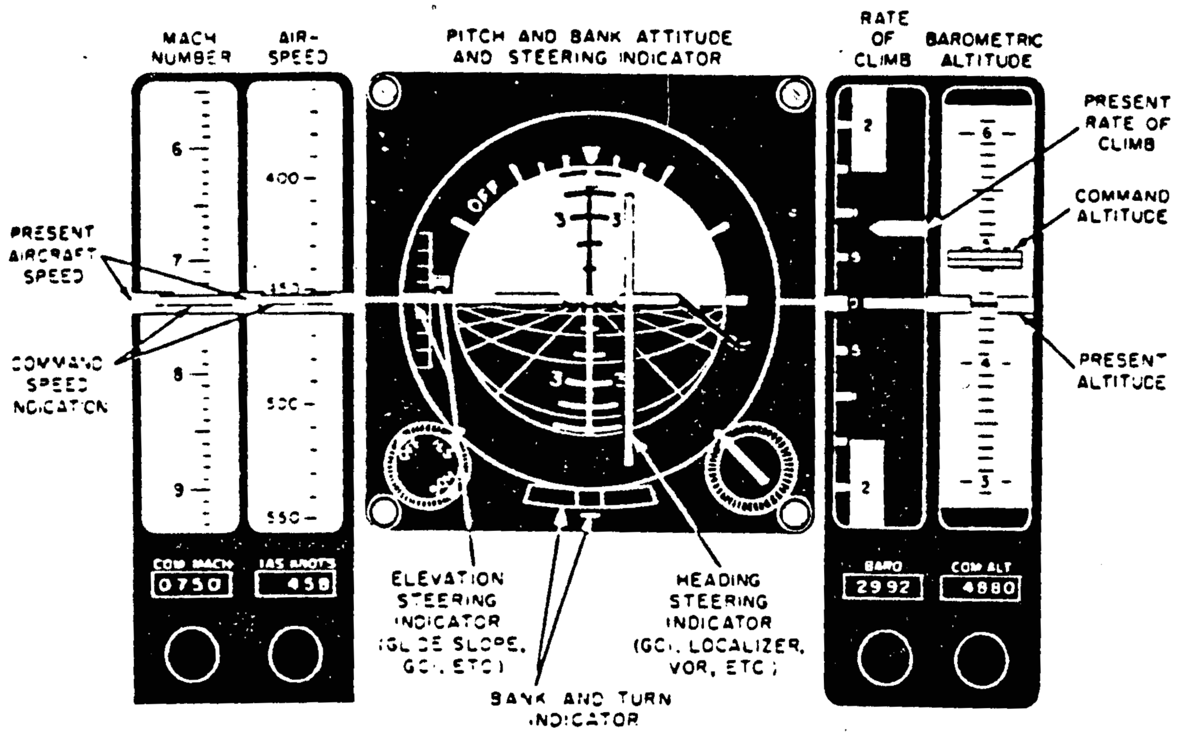


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Figure 10: Integrated Instrument Display

The "forward-looking" portion of the panel is planned to provide a single frame of reference in interpreting instrument indications by providing a common center line that extends across all instruments in the row (see Fig. 13. 6). When the aircraft goes into a climb, for example, changes in all the rate and displacement indications (displayed side by side) are consistently related to the center reference line and to the pilot's control movement. Insofar as possible, scale displacements are in a single direction. Note also that actual performance data and desired performance values are displayed so that the pilot does not have to remember specific values. Instead, he flies the aircraft so as to keep the indices aligned across the reference line.

(Extract from "Vision in Military Aviation"
Wulfeck et al 1958. WADC-TR-58-399
p. 285)

There was another popular feature: the moving tape formats for airspeed and altitude. By the use of cursors shaped like Captain's Bars, one could mark some preselected parameter sufficiently to not require foveation; i.e., could monitor it with peripheral vision. The numbers on the tapes were such that the smaller airspeed was at the top and vice versa for altitude. While flying straight and level, the cursors formed an even line with the ADI's horizon. If one drifted off, however, say inadvertently entered a descent, as airspeed increased, the left (airspeed tape) cursor would move up as the higher airspeed came into view; the horizon line would move up as attitude changed; and the altimeter cursor would move up as altitude was lost and the lower altitude moved into view. The opposite would happen for an ascent. This provided a very nice redundant cue to attitude and facilitated the cross-check. Once pilots learned how to interpret and use the moving tape format, they generally preferred it to round dials. Mr. Pete Lovering may discuss this device tomorrow.

Another approach is that of Dr. Richard Malcolm, in his Peripheral Vision Horizon Display, an attitude indicator projected onto the instrument panel that is wide enough to be monitored out the corner of the eye. It enables attitude awareness by the ambient mode thus freeing up the focal mode for tasks requiring focal mode processing; this has significant potential not only for reducing spatial disorientation but also for reducing cockpit workload. Dr. Gillingham has formally tested this device in the lab and demonstrated an improvement in instrument approaches.

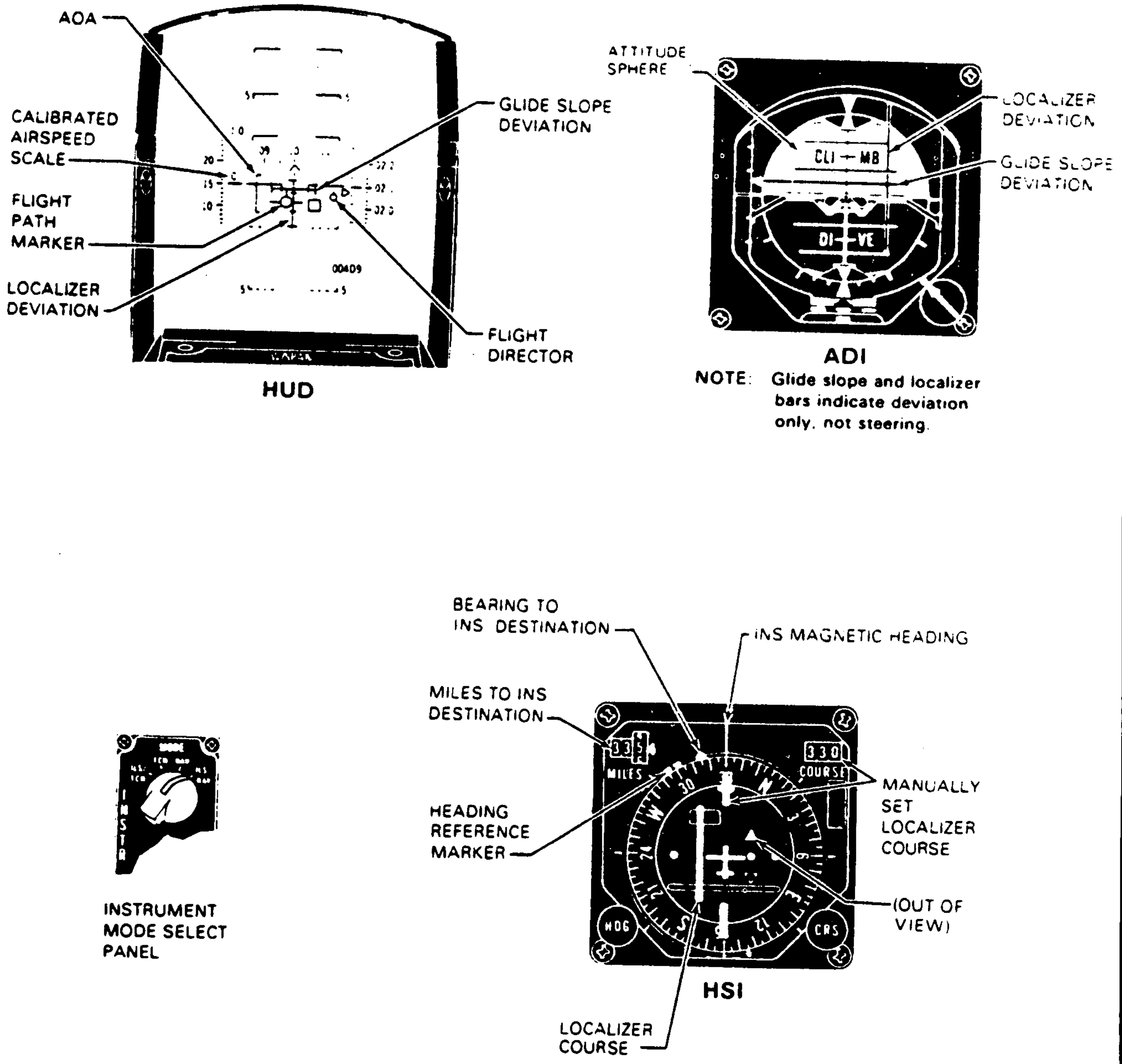
There's a second source of attitude information--the SAI--about which we'll hear more tomorrow from Mr. Dick Geiselhart. There are some issues regarding the position of this instrument relative to the primary ADI, as well as basic reliability.

Before proceeding to the third source of attitude information, I'd like to digress a moment on the characteristics of man versus displays, and make some remarks about attitude depiction. As you'll hear from Dr. Malcolm and others this afternoon, man is basically a pattern recognizer, from birth on. The more that you can organize information for him visually, the faster he can acquire and understand it, which is why a picture is worth a thousand words. When a pilot looks at a display, he usually wants to know only whether the parameter it represents has changed, and if so, in which direction, how much and how fast; i.e., he wants trending information. He also likes limitations cues--whether the parameter is too low, too high or right on.

The problem with digital, symbolic and alpha-numeric displays is that they require focal mode to read, decode and integrate, and provide no inherent trending nor limitations information. Analog displays generally overcome these objections but can be misread, as illustrated by the old altimeter which could be misread by 10,000 feet. Finally, any display which traps the pilot's attention can kill him.

Instrument Modes (Typical)

ILS/NAV US DE NO



NOTE: Glide slope and localizer bars indicate deviation only, not steering.

Figure 11: ADI and HUD

Now, let's talk a moment about attitude depiction in general (Figure 11). The way we depict attitude generates an important human factors problem: reversed roll-sensing. The most commanding part of the ADI is the part that moves - the horizon. In order to "level" the horizon, you must move the stick in the direction opposite to its desired motion. This reversed roll-sensing is one reason it takes so long for a pilot to learn to fly instruments, so that the correct response becomes automatic. Still, this is an unnatural act, and even test pilots with over 2500 hrs in fighters have confided that when coping with an unusual attitude, they must first tweak the stick to see which way the ball moves before initiating recovery. So for some, perhaps most of us, if truth be known, the response never does become automatic. Those who learn to cope successfully often do so by imagining themselves inside the aircraft, looking out at the world through a porthole the size of the ADI window, which is why it's called an "inside-out" display.

At least the ADI is an attitude indicator. The little "W" (waterline symbol) which is fixed, tells where the aircraft is pointed relative to the horizon, which moves. On the sphere, the sky is blue, surface brown and horizon unmistakably depicted, and the field of view approximates 90°-110° of the sphere.

This brings us to the third source of attitude information, which is on the HUD. The HUD is also an inside-out display with reversed roll-sensing like an ADI, but it is <u>not</u> an ADI. The aircraft symbol, , which moves in pitch and yaw (but not in roll) tells not where the aircraft is pointed but where the aircraft is going. It is really an inertially derived flight path marker. (Some HUDs also display a "W" waterline symbol or gun cross indicating where the aircraft is pointed; the difference between where the aircraft is going and where it is pointed constitutes angle-of-attack, Fig 12A.)

On the HUD, there is no clear distinction between sky and surface--the only difference being the type of lines on the pitch scale: solid for positive, dashed for negative. The overall pattern of the scales is symmetric about the 0o pitch line (horizon line) which, itself, is not much longer and therefore hardly more commanding than any other pitch line. The horizon line in most HUD's is straight, whereas all other pitch scales have "tails" pointing toward the horizon.

In trying to determine one's attitude from the HUD, it is not always immediately apparent whether one is upright or inverted, or climbing or diving, or if so, to what general extent, because the scales all look about the same.

Whereas the ADI gives a 60-110° FOV (the big or macro-picture), the HUD provides only a 14-20° FOV, or in the case of the F-16, 16°. This is the micro-picture; it is like taking a 16° circle out of the ADI, and expanding it

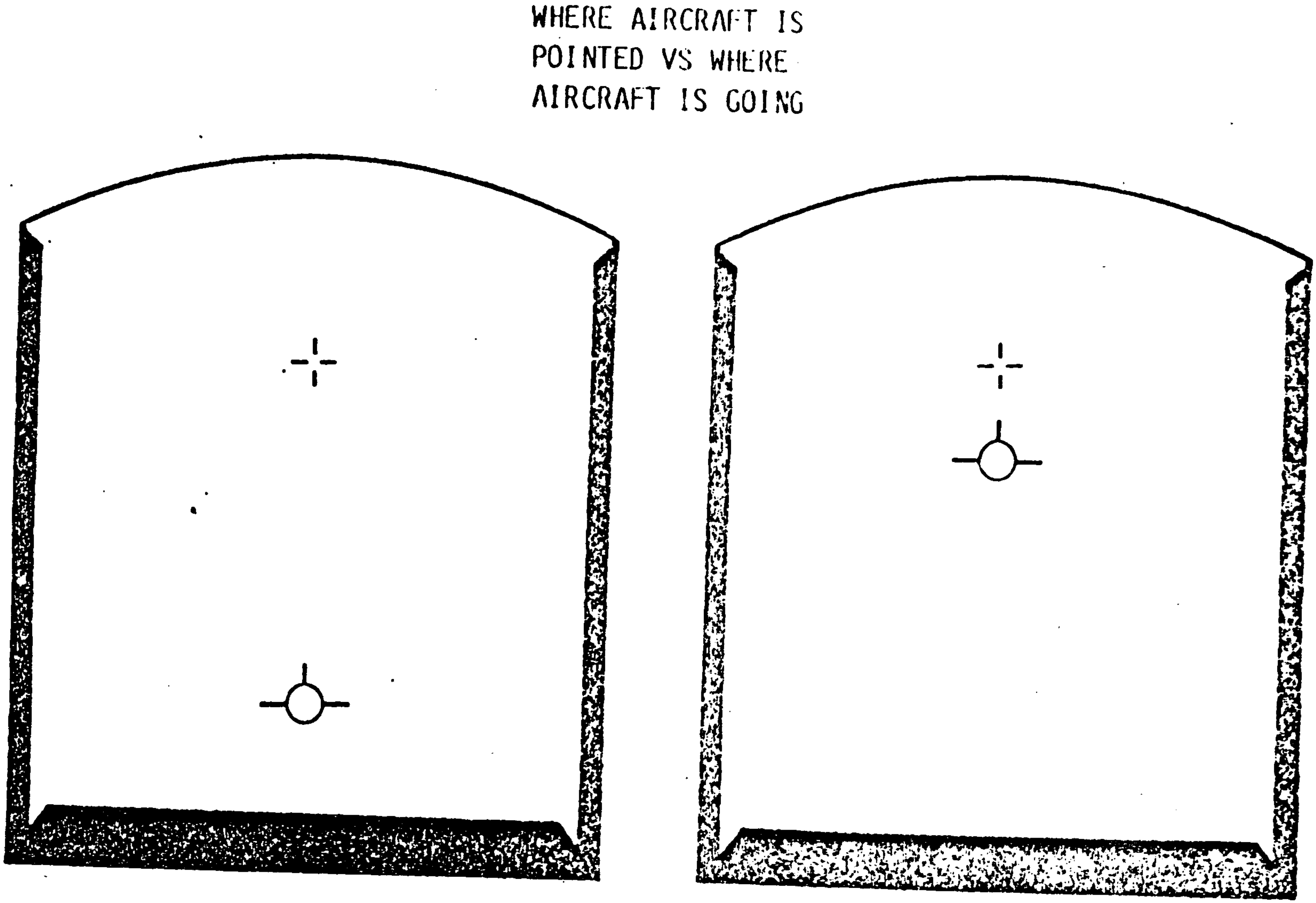


Figure 12A: HUD depicting gun-cross (where aircraft is pointed) versus Flight Path Marker (-○- , where aircraft is going)

PITCH SCALE
SLEWING OFF
COMBINER

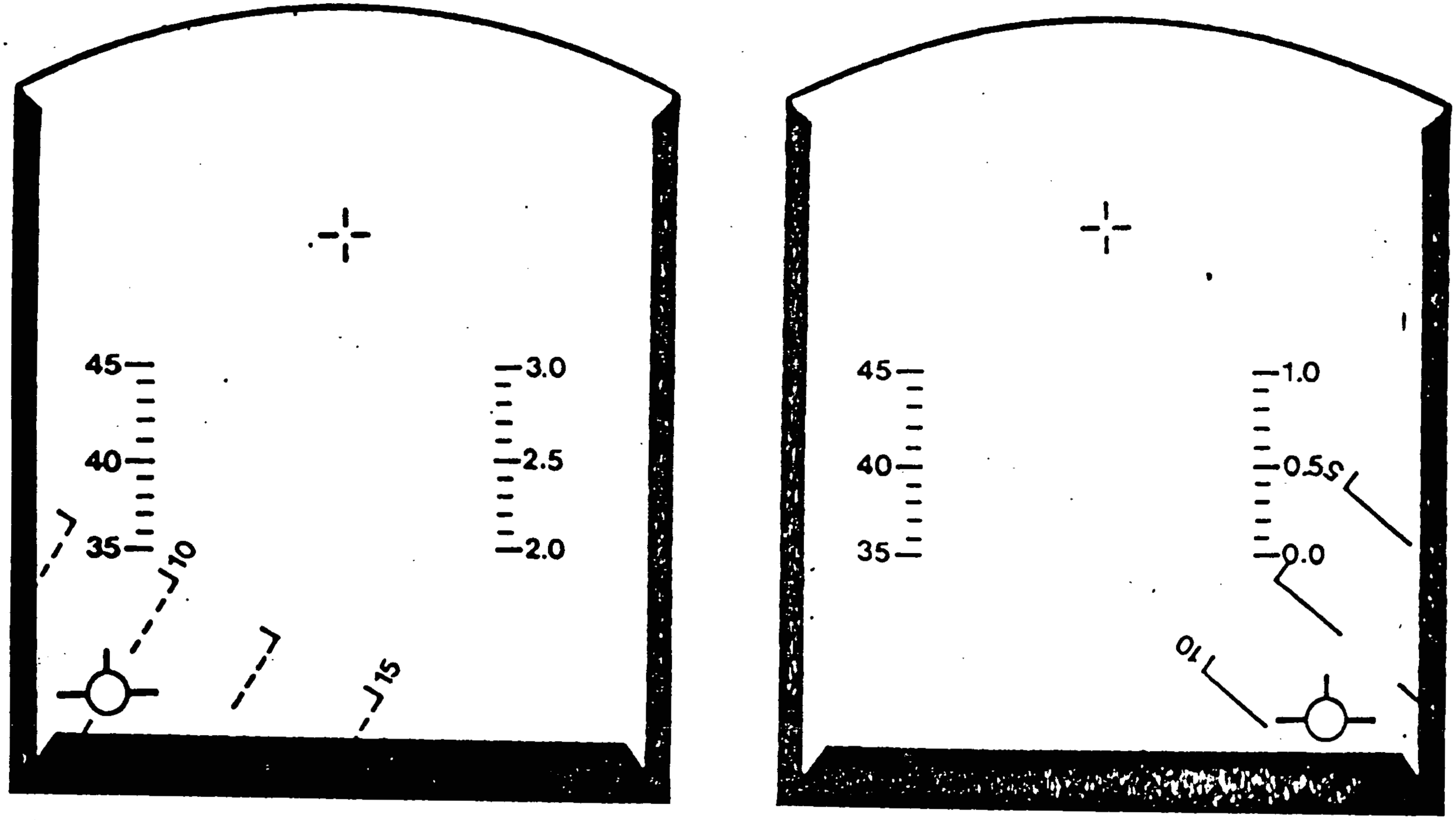


Figure 12B: HUD Pitch Scale slewing off face combiner

F/A-18A Navigation HUD Display

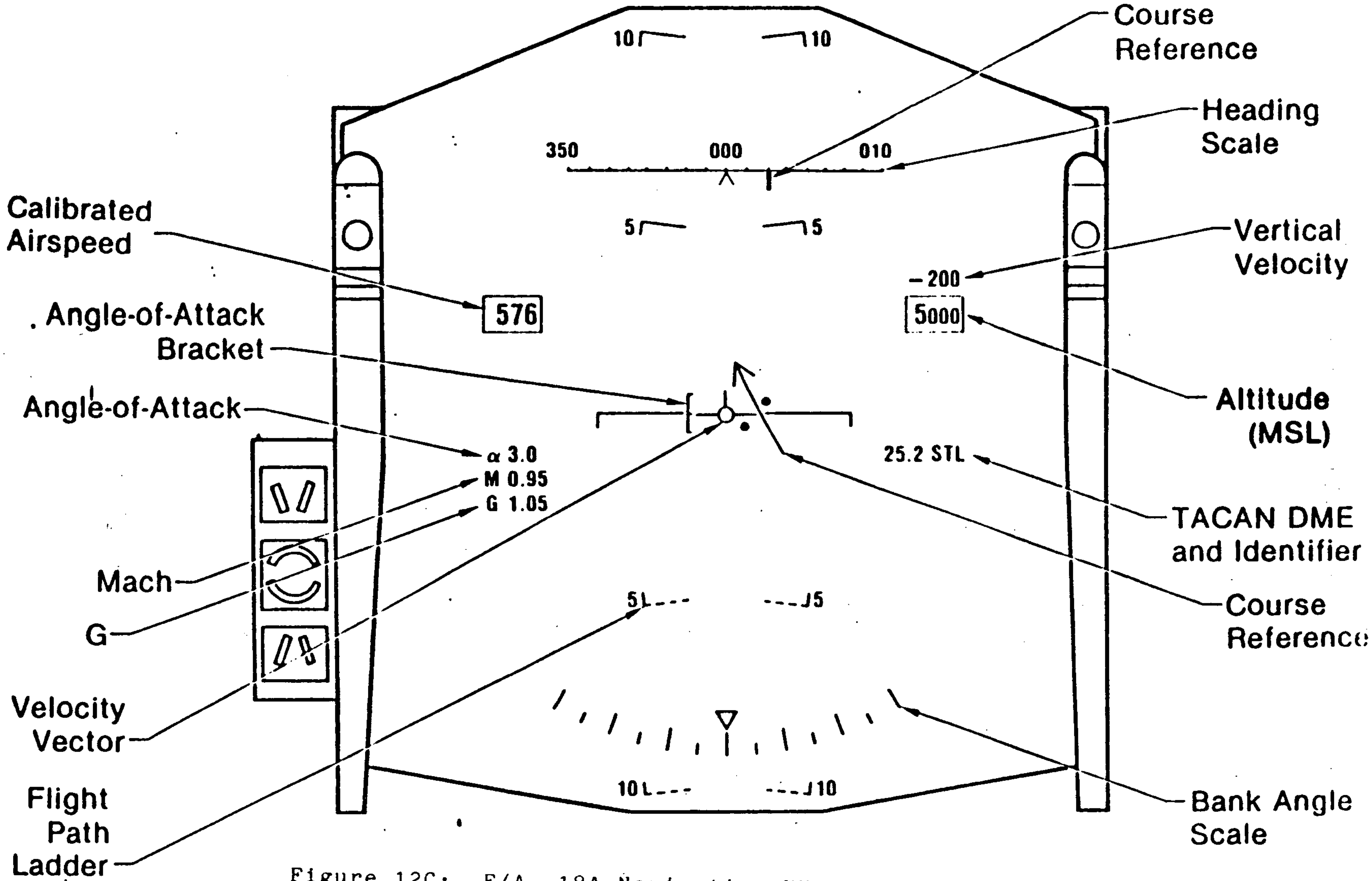


Figure 12C: F/A -18A Navigation HUD Display over the face of the combiner. It not only magnifies the scale to 1:1 with the outside world, it also magnifies the dynamics of the FPM and, in particular, the Flight Path Scales (FPS, also called pitch scales). Whereas the FPM moves as if on a pendulum, suspended from the gun-cross, the FPS revolves around the FPM. The dynamics are such that at high pitch or roll rates, or in high cross winds, the FPS can nearly slew off the face of the combiner (Fig 12B) and may become unreadable. In other words, at rapid roll or pitch rates, the FPS does not hold still for interpretation. Thus, the first step in recovering from an unusual dynamic attitude via the HUD is to first stop the roll or slow the pitch rate so you can read the numbers on the FPS! This takes some finite amount of time. The next steps are combinations of pulling to the horizon and rolling upright, or rolling upright and pulling to the horizon. There are cues on the FPS's to help you reach the horizon: in the F-16 HUD, the FPS's have horizon pointing tails; in the F-18, the entire FPS is angled like a chevron, (Fig 12C), aimed at the horizon, forming a channel. However, there is still the problem of determining which way is upright. Since there is no clear distinction between sky and surface on the HUD, you must reduce the dynamics sufficiently to tell whether the FPS's are solid (for positive pitch) or dashed (for negative). Again, this takes some finite amount of time. Furthermore, since there's nothing intuitively obvious about the symbology for upright vs inverted, it's entirely possible to recover to straight and level, inverted, and not recognize it for some time (Fig 12D).

Although the Flight Path Scale yaws and rolls (and, of course, scrolls up and down in pitch) over and off the combiner, there is a considerable quantity of symbology and scale that does not move: for example, the airspeed, heading and altimeter scales as well as the digits for G and mach, and other symbols for avionics, radar and weapons modes are fixed; and being fixed, they constitute a stationary frame of reference. With the preponderance of evidence to the eye being that nothing is moving up there, motions of the FPS may not even register, especially if off center or nearly out of view. (Motion of the FPS will, of course, register as motion, but not necessarily as aircraft motion.) In some cases, the FPS can actually generate more "quality of horizoness" when rotated 90° (Fig 12E), so for all these reasons, HUDs are less than optimal attitude instruments.

Another problem area of the HUD is attention allocation--the effectiveness of information transfer and the potential to trap attention. Digital formatting aggravates this because of tying up the focal mode. Furthermore, your span of focus is too narrow to read more than one parameter at a glance. If you want 4 or 5 different parameters, you must make as many eye stops and then you still must decode and integrate it. So, despite the clustering of information, it doesn't invariably speed up the cross-check. As a matter of fact, many pilots feel there's too much stuff up there (Fig 12F) and the first thing they reach for is the declutter switch.

RECOVERY TO S&L INVERTED WITHOUT REALIZING IT

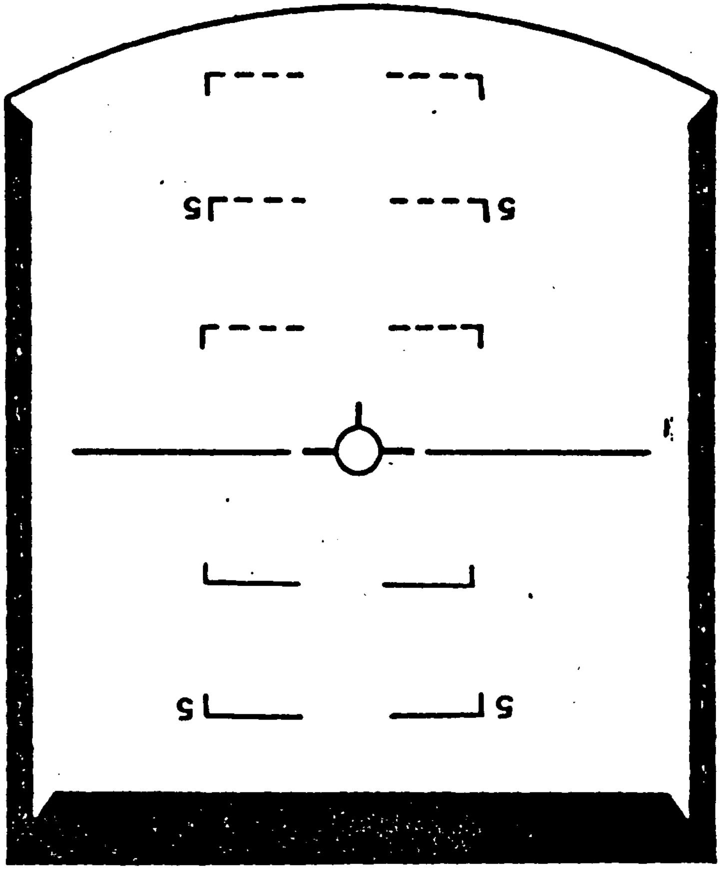


Figure 12D: HUD depicting recovery to straight and level inverted without realizing it

PITCH SCALE =
MORE QUALITY OF
"HORIZONESS" WHEN
ROTATED 90°

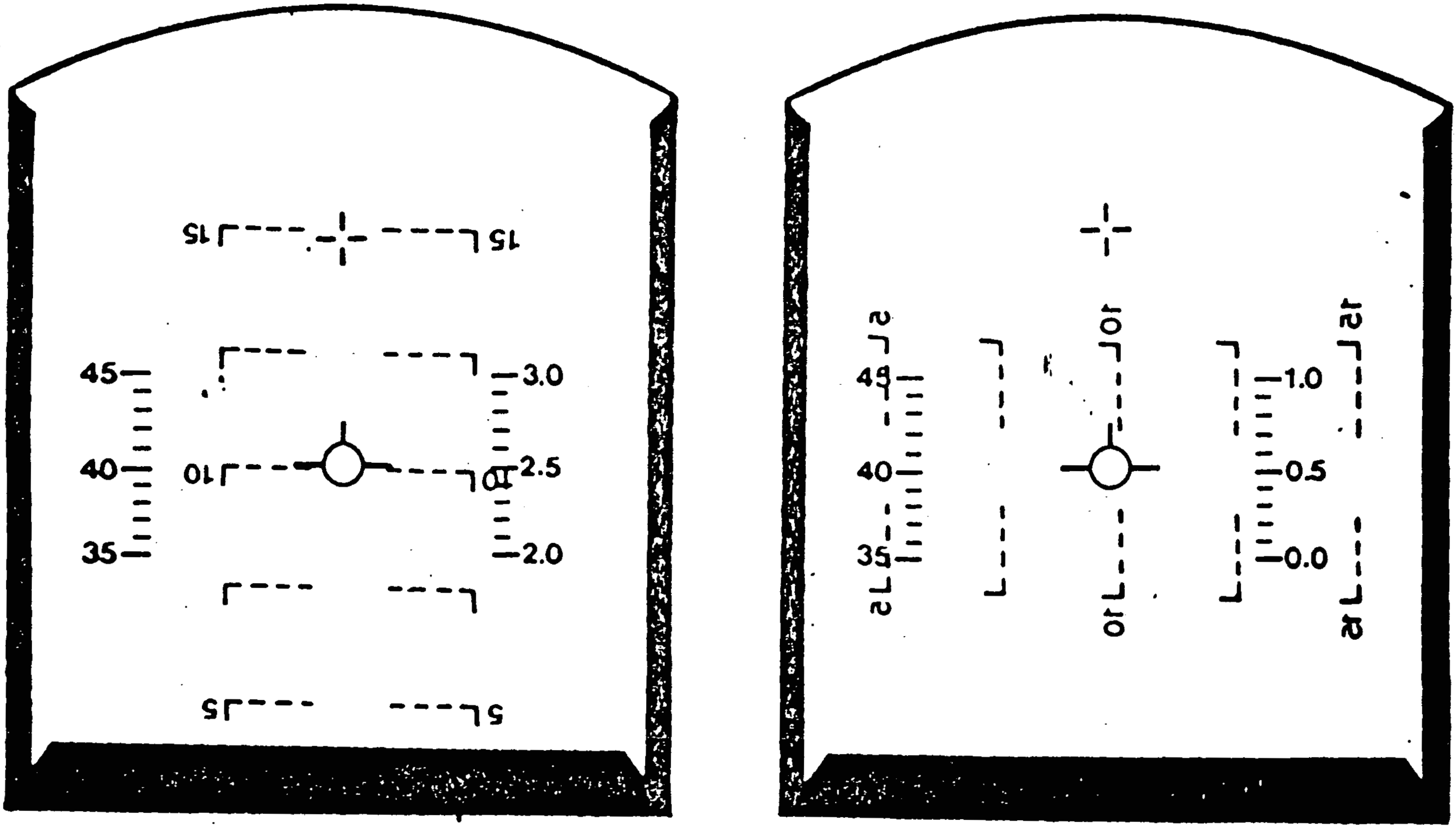
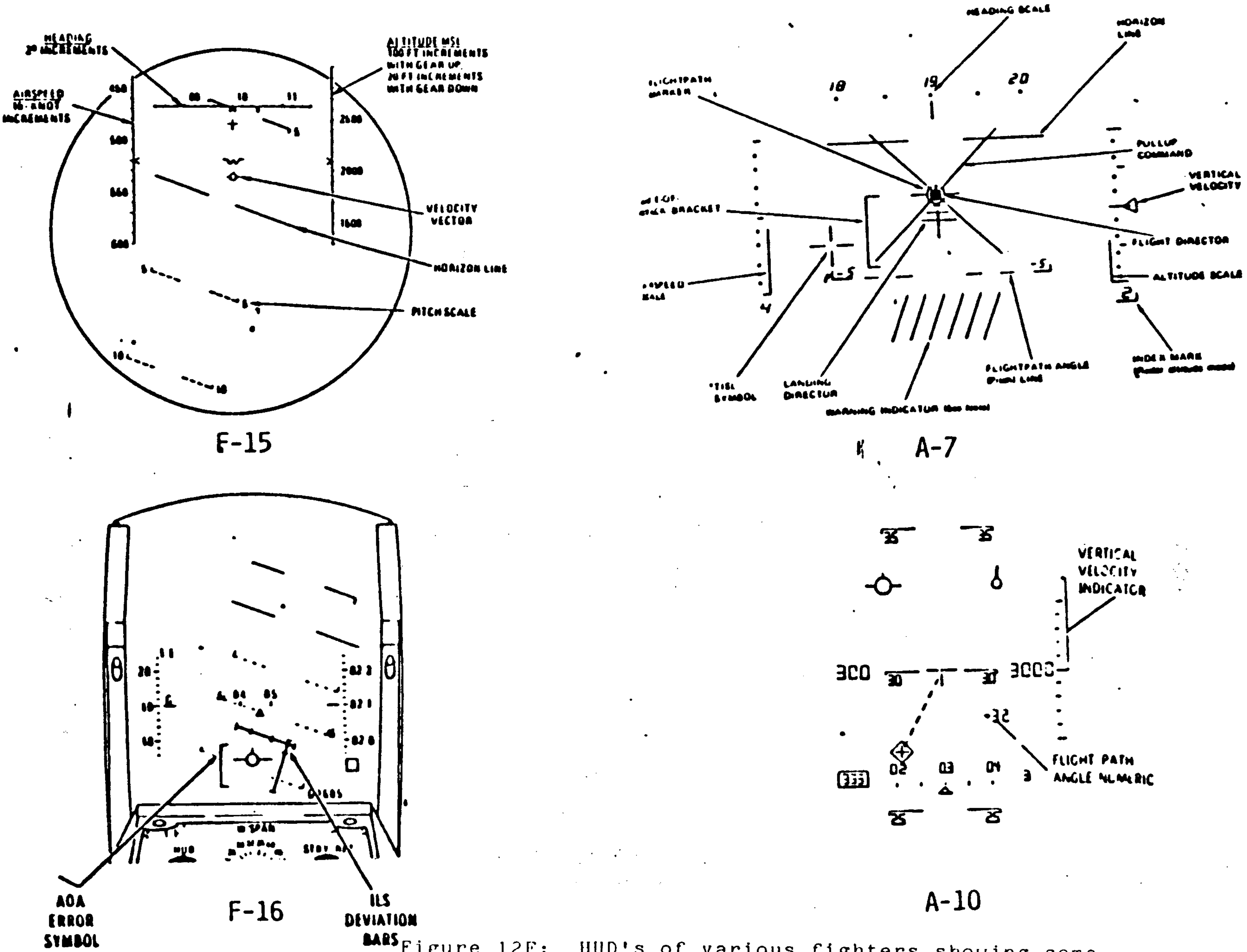


Figure 12E: HUD Flight Path Scale showing more "quality of horizoness" when rotated 90°

HUD DISPLAYS



F-15

A-7

F-16

A-10

Figure 12F: HUD's of various fighters showing some of the tendency to clutter

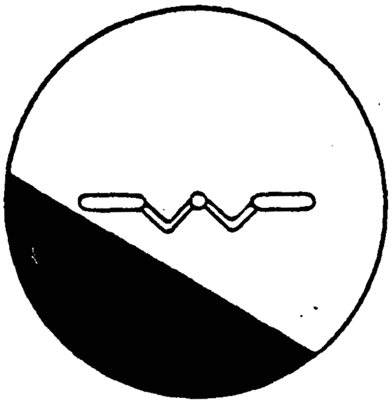
Another phenomenon regarding HUDs is the tendency to stare at all that symbology and become mesmerized by it, deceiving yourself that you're processing all that information when, in fact, you are not. They even have a name for this: "HUD Hypnosis."

Another problem arises because HUD symbology is projected into space as virtually imagery. Looking at the virtual imagery of the HUD is like looking at something through the knothole in a fence; various combinations of the pilot's eye position and the FPS position may move it beyond his view. Another point, although the HUD imagery is collimated to infinity, the eye does not necessarily focus to infinity when looking at the HUD. In fact, the eye tends to focus at an intermediate range corresponding to its own resting dark focal length. For many pilots with 20/20 vision, their dark focus (the distance to which they accommodate in the dark) is only 3 or 4 feet. As you will hear from Joyce Iavecchia and Stan Roscoe, this has implications for clearing the flight path.

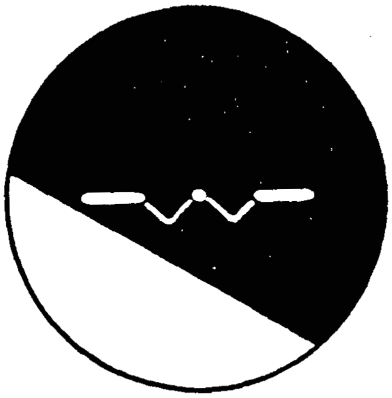
Finally, looking through the HUD in visible precipitation or moving lights can create a disorienting vection sensation.

This is not to say that you can't fly instruments on the HUD or recover from unusual attitudes. You can fly an entire mission on the HUD or an entire airshow on only the HUD--including loops, rolls and all sorts of aerobatics, <u>provided you keep up with the maneuver</u>. What's difficult is attempting to go from some unknown, unrecognized or misperceived attitude to the HUD to recognize the problem, sort it out and cope. The HUD is simply not designed for that. The HUD evolved from the gunsight and is designed specifically to enable maneuvering against a visual scene, which it, in effect, calibrates. It's ideal for precision ordnance delivery or for clearing terrain. Because the Flight Path Marker (FPM) organizes so much information for you, you simply keep the FPM above the obstructions. Or even precision approaches: to shoot a 2.5° glide-slope, simply keep the FPM at -2.5°, and you're wired. But the HUD was not designed nor intended for the recognition of or recovery from unanticipated, unusual attitudes.

The following mishap illustrates the confusion potential of the HUD. It involved a student pilot on his third night ride, a bomb drop on a pitch black range. The mission was uneventful till just following bomb release, when the student established an upright left climb and flew into an unforecast cloud. Within 30-40 seconds of entering that cloud, he rolled from an upright left climb, 180° to an inverted right dive, and impacted with no further call nor attempt to eject. The Mishap Investigation Board suspected a distraction, and sure enough, a warning light requiring him to throw a certain switch was found to have been illuminated at the time of the crash. Though we'll never know what was going on in his mind, it's likely his attention was trapped in coping with this "emergency".



At the moment the aircraft entered IMC, the ADI would have looked something like this.



At the moment of impact, the ADI would have looked like this... The barrel of the ADI is less than 2" in diameter, as in this figure. It is located between the knees, 24" to 34" from the Design Eye Point. Could it be possible to confuse these indications, such as at night, with canopy reflections?

Note: Horizon line subtends an angle of only 3.4 to 4.8 at the eye - not particularly commanding.

Figure 13: ADI's Depicting Upright Left Climb & Inverted Right Dive

Suppose he'd looked at his ADI the instant he entered that cloud and again the instant before hitting the ground (Figure 13). Is it possible, with the glare and reflections, that he could have confused depictions, or even made a roll-reversal?

But suppose he'd glanced at his HUD at the same instant, realizing that in the ordnance delivery mode (which he was using) the pitch scale slews over the combiner and would not necessarily be centered as depicted in Figure 14. Since this aircraft does not "talk" to the pilot nor alert him of any change, he may not have been suspecting that anything had changed--he could easily become a victim of the element of expectancy, see what he expects or wants to see, and simply misinterpret the depiction. We think he could have been a victim of this more subtle and insidious form of spatial disorientation, more lethal because it fails to alert its victims to even question attitude, hence, they delay cross-checking attitude till it's too late. Some refer to this as "spatial misorientation."

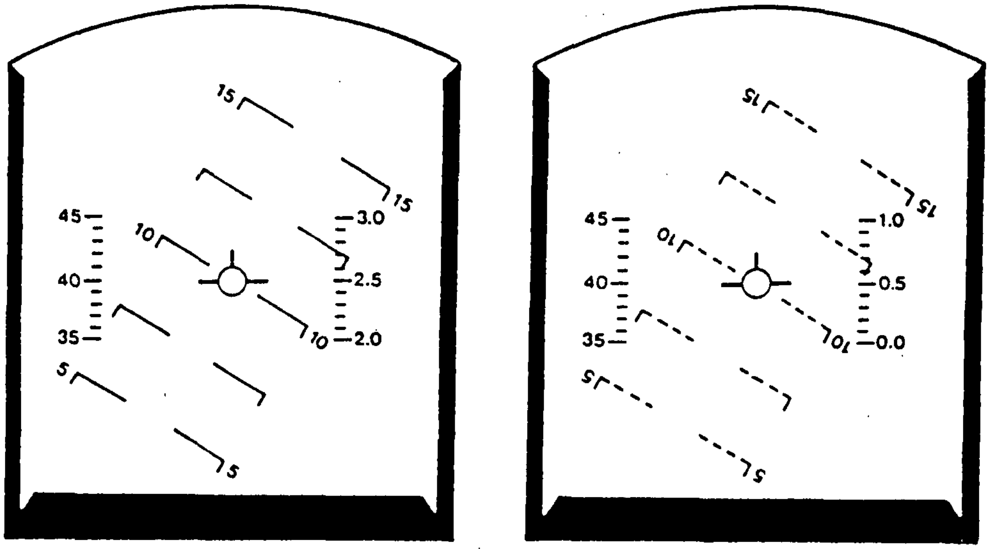


Figure 14: HUD's Depicting Upright Left Climb & Inverted Right Dive

In some HUDs, the pitch scales are angled, like chevrons, pointing toward the horizon. While this may improve orientation toward the horizon, as long as the pattern is symmetric about the horizon, it does not necessarily avoid the confusion of upright-inversion, as per Figure 15.

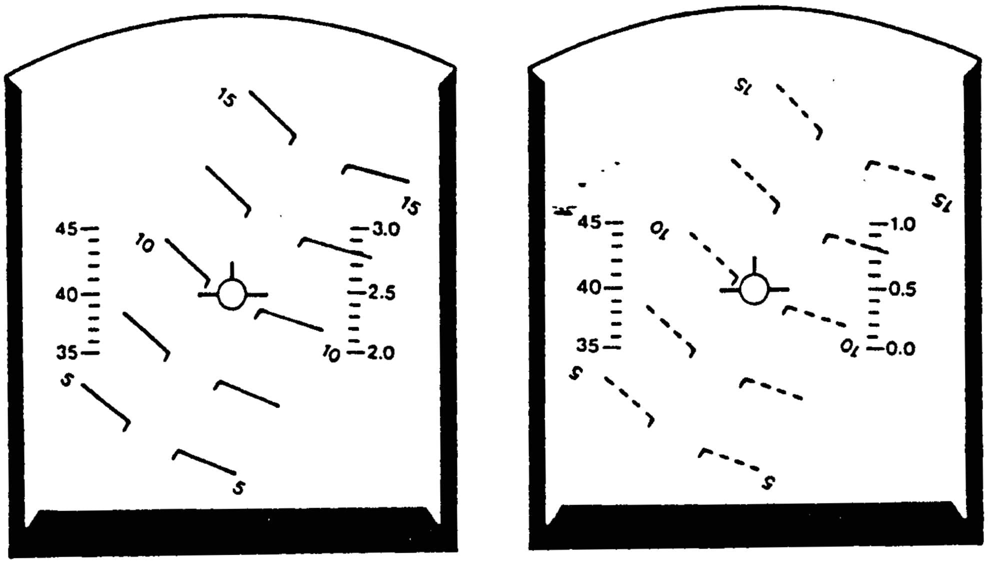


Figure 15: HUD's with Angled Flight Path Scales, Depicting Upright Left Climb & Inverted Right Dive

To reiterate: The ADI is designed for the recognition of and coping with unusual attitudes. The HUD is not, and such actions can be very difficult on the HUD.

This is not to say the HUD could not be improved upon for attitude recognition. As a minimum, two changes would be needed:

a. Since the FPM is so commanding, it would seem reasonable to make it into a roll cue. This could be done by simply adding to it a zenith-pointer, as per Figures 16 A,B,C. The star is Dr. Malcolm's idea--to add "innateness" to the cue (stars are up, in the sky).

b. The relative simplicity of pitch scales fails to cue regarding angle from the horizon, at least when the pitch lines are straight. Admittedly, using chevrons with angles increasing with offset from

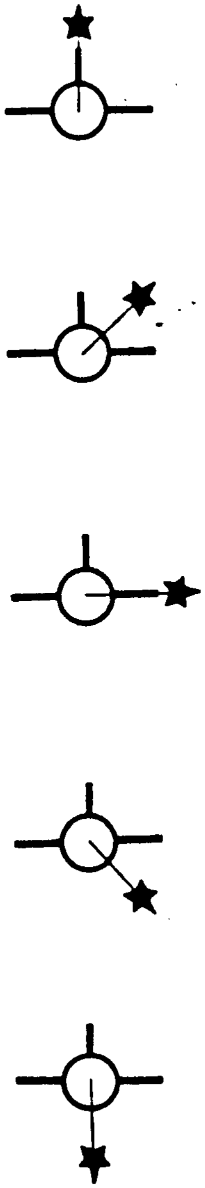


Figure 16A: HUD Flight Path Marker Showing Zenith Pointer

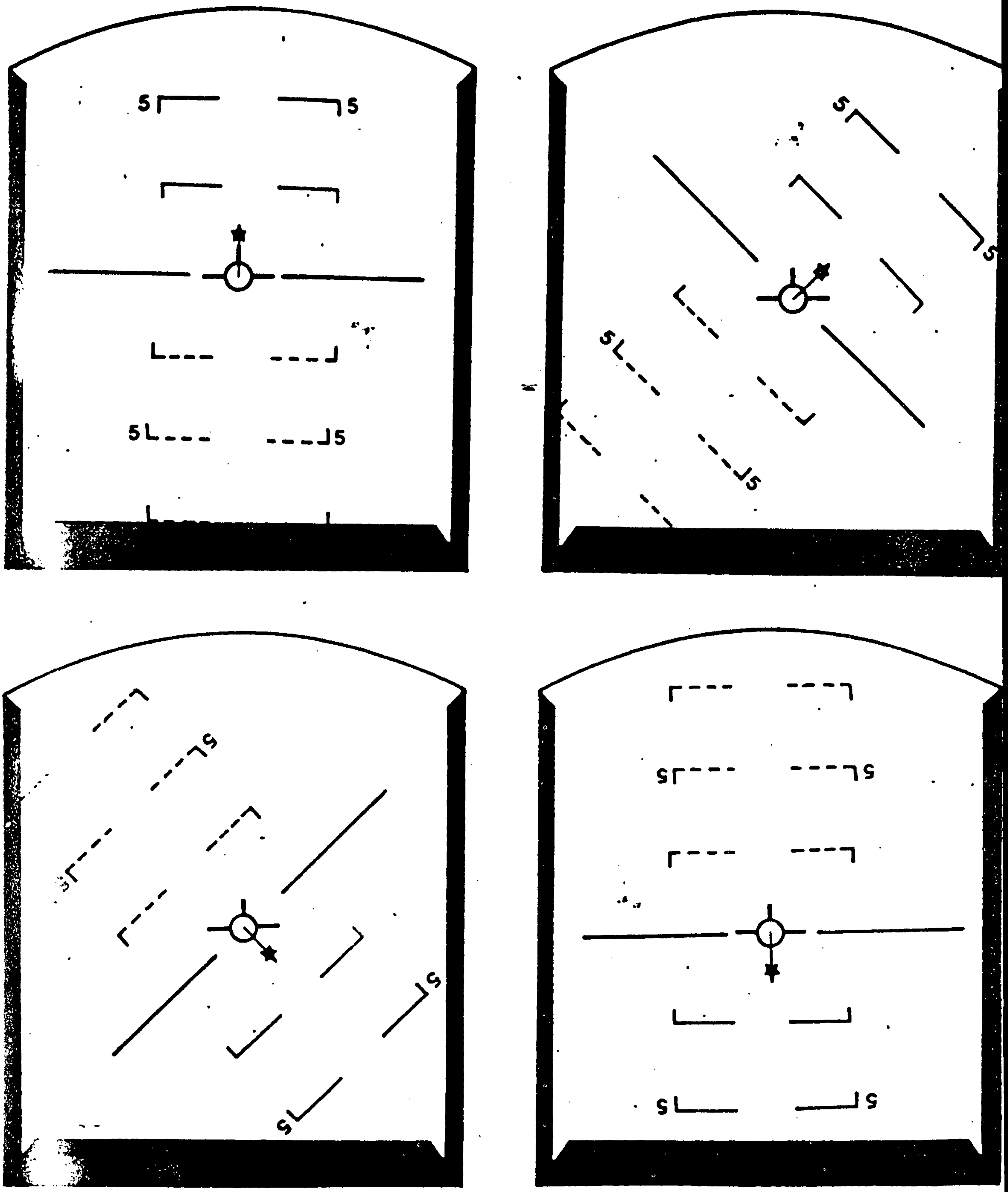


Figure 16B: HUD FPM showing (clockwise) S&L Upright, 45° Left Bank s&L Inverted, 135° Left Bank

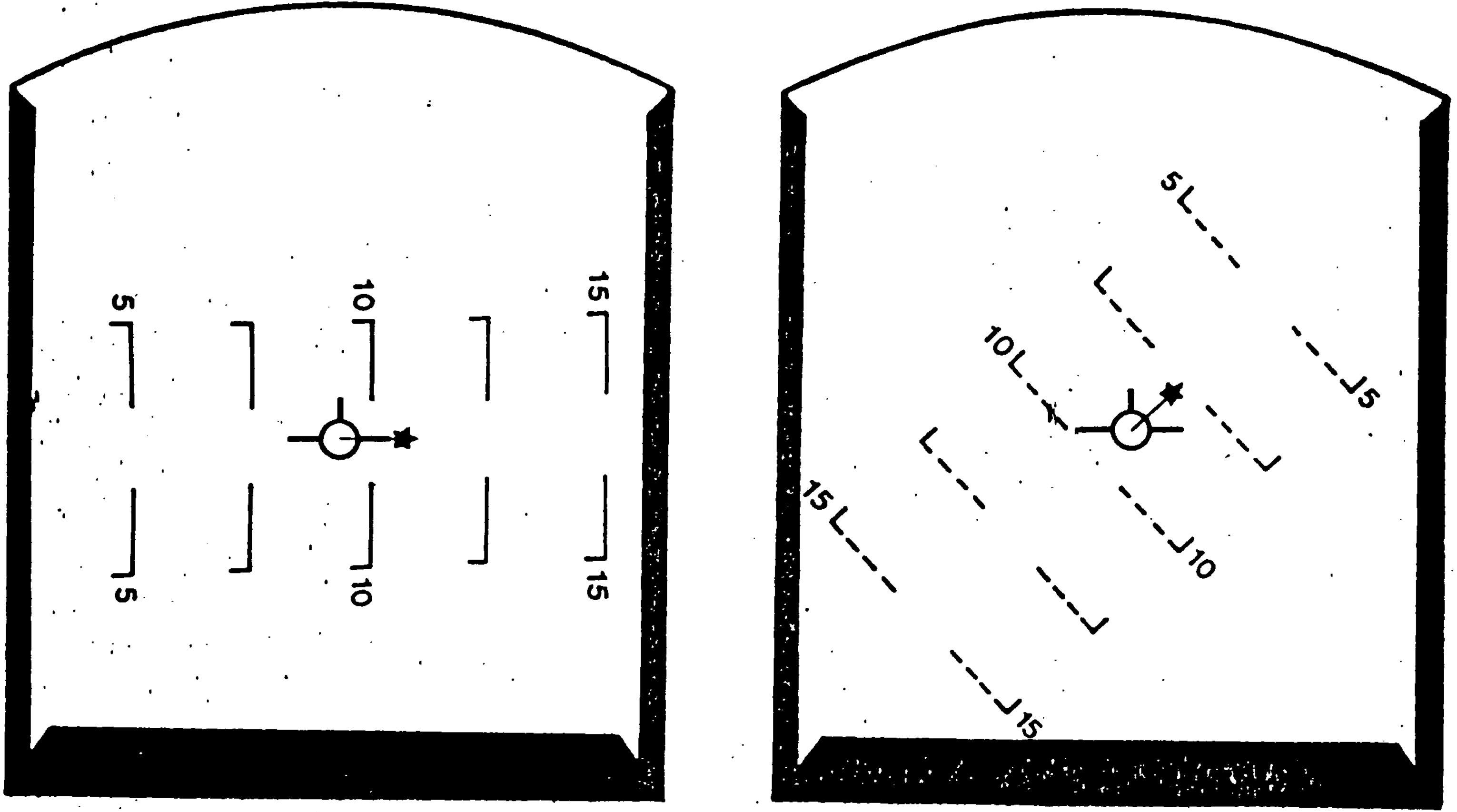


Figure 16C: HUD FPM showing 90° Left Bank at 9° climb; 45° Left Bank at 9° Dive

VERTEX POINTER
ON THE FPM

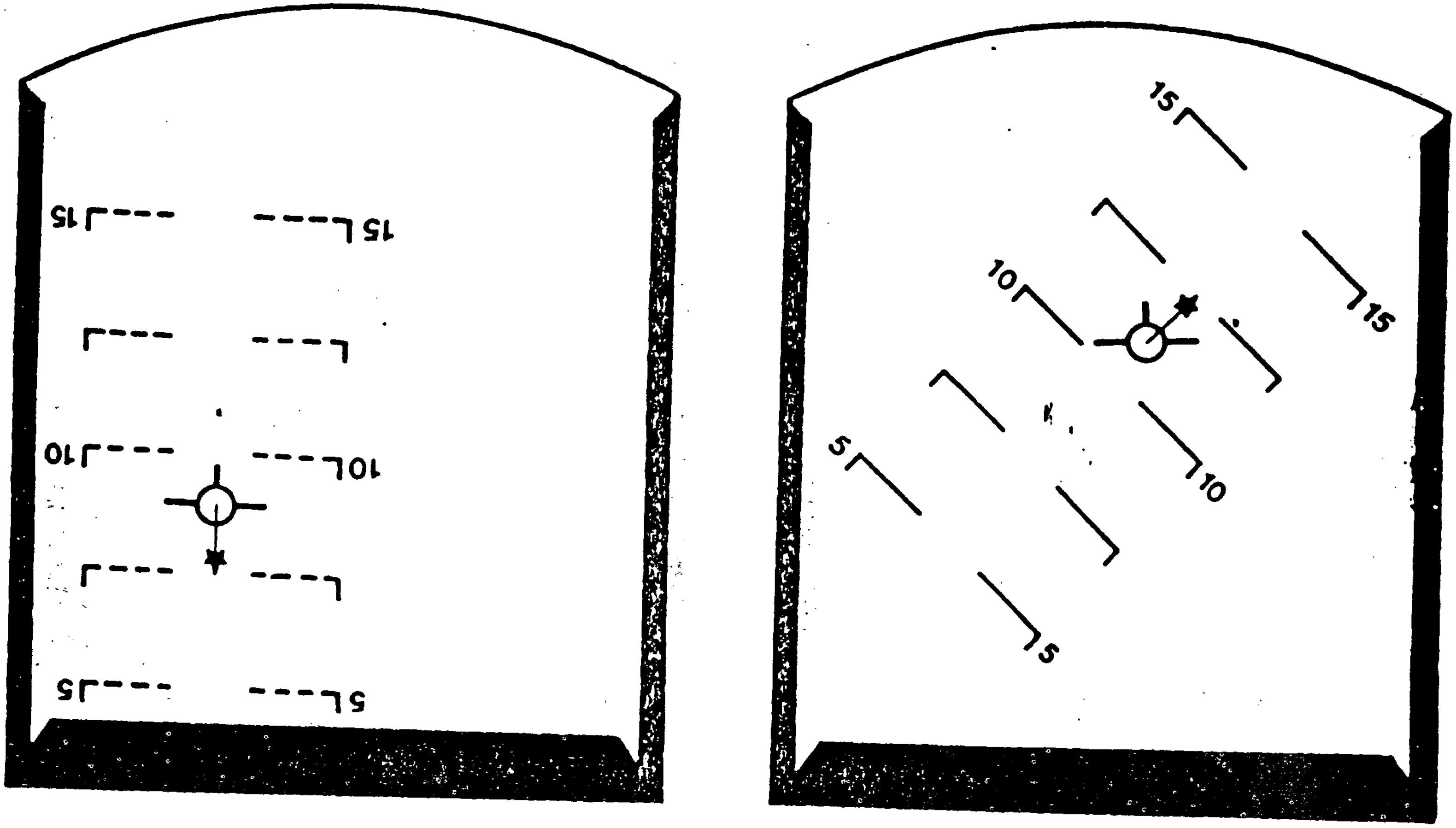


Figure 16D: Vertex Pointer on the FPM

HUD PITCH SCALE SHOWING
RADICAL CHANGES FROM POSITIVE
TO NEGATIVE & WITHIN NEGATIVE

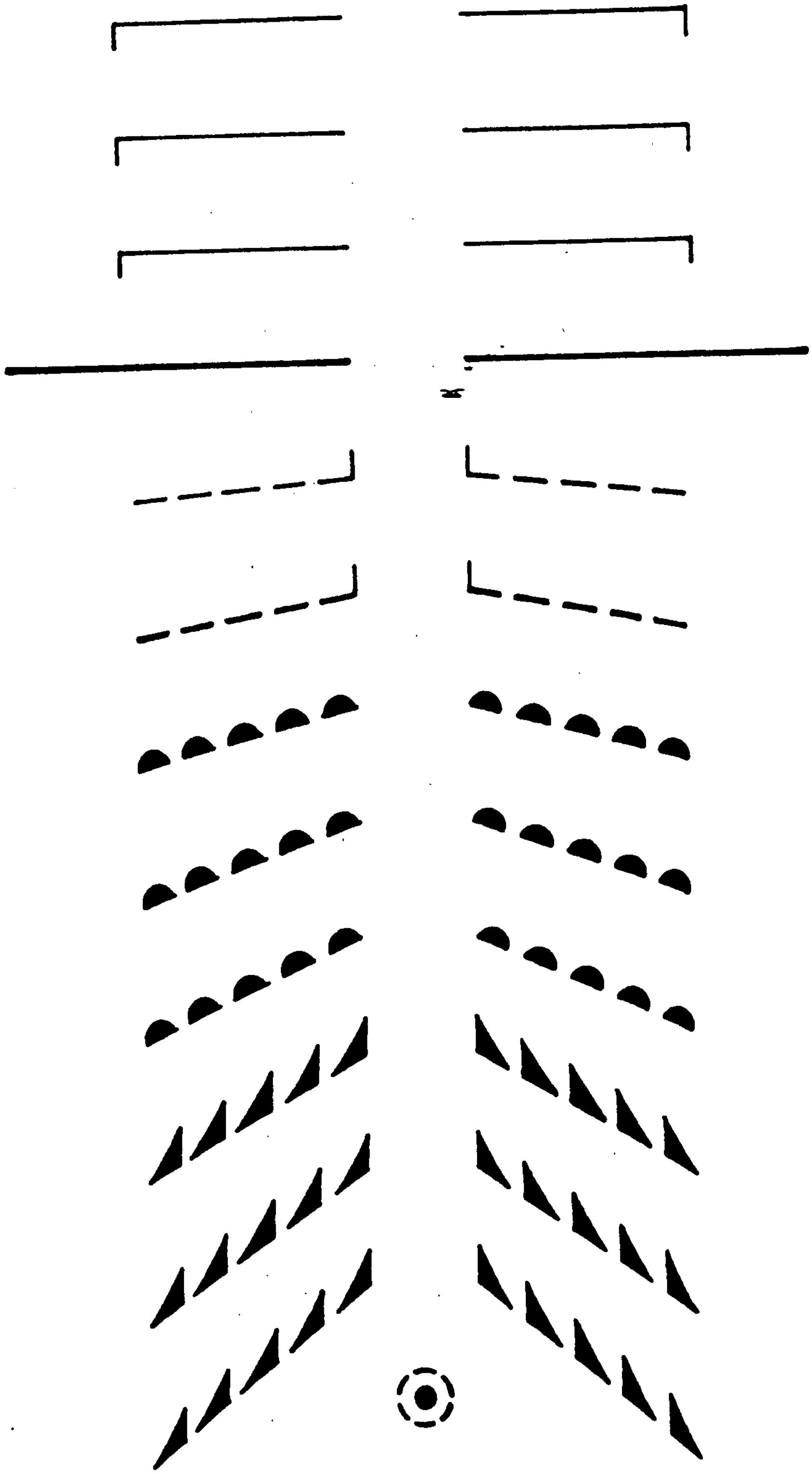


Figure 17

the horizon does provide some cue. But keeping with the premise that humans are basically pattern recognizers, why not alter radically the pattern of positive from that of negative pitch; and since negative pitch is more time critical than positive, why not alter again the pattern of pitch scales from one range of negative to the next, the steeper becoming more urgent, as per the "Shark's Jaws" (Figure 17 A,B)? At least it should cue him to go immediately to the ADI, which is the prime recognition and recovery instrument. Dr. Robert Taylor of the United Kingdom will discuss HUD pitch scales tomorrow.

Arrangement of certain instruments has also been implicated in mishaps, e.g., standby attitude indicator (SAI) and the altimeter. One mishap implicating the SAI involved the lead of a 3-ship to the range. Sandwiched between cloud layers at 7000', shortly after takeoff, lead announced he had a problem and initiated a hard 180° turn, presumably to return to base. In so doing, he entered a cloud, from which he shortly emerged in a dive, entering lower clouds obscuring mountains. There was no further call nor attempt to eject, but positive control movements indicate he was conscious immediately before impact. The Mishap Investigation Board was unable to ascertain the nature of the problem. One of the only things found wrong with the aircraft was a mismatch of over 100° between the primary ADI, which correctly depicted a 67° dive, and the SAI which erroneously indicated a 40° climb. This pilot had a reputation as a strong instrument pilot. Had he been referencing the primary ADI, the Board was certain he would have recovered (or at least attempted). Their conclusion is that he was referencing the erroneous SAI, located closer to the eye line. This raises the question of whether it would improve matters to co-locate the ADI and SAI, either side-by-side or vertically.

As hard as some things are to learn, once learned, they're even harder to forget. This applies to the location of switches, ejection handles and even instruments, in this case, the altimeter. The mishap pilot had just completed his replacement training unit course and had 50 hours in models with the ADI, ASI, ALT, and HSI instruments arranged in a "T" (Figure 9). He then arrived at his new base to fly newer models with those instruments arranged in a "square" (Figure 19). The modification was accomplished by moving the altimeter from the right of the ADI, to the left of the lower horizontal situation indicator (HSI), placing it even deeper into the cockpit.

Having been at his new base about a month, this pilot was assigned to fly a series of surge sorties, in which he awakened at 0200, briefed at 0300, launched at 0400, flew some intercepts, then landed, flew another sortie or two, then headed back to quarters to try to get some rest for the next early morning go. The mishap occurred on a pitch black night over a pitch black range. This was his fourth morning, so first of all, if he wasn't tired, he should have been (although probably no more so than most of the others). Second, he'd been having difficulty acquiring his target, which was his lead

COMBINATION OF VERTEX
POINTER ON FPM PLUS
RADICAL CHANGE IN FLIGHT PATH
SCALES FROM POSITIVE TO NEGATIVE

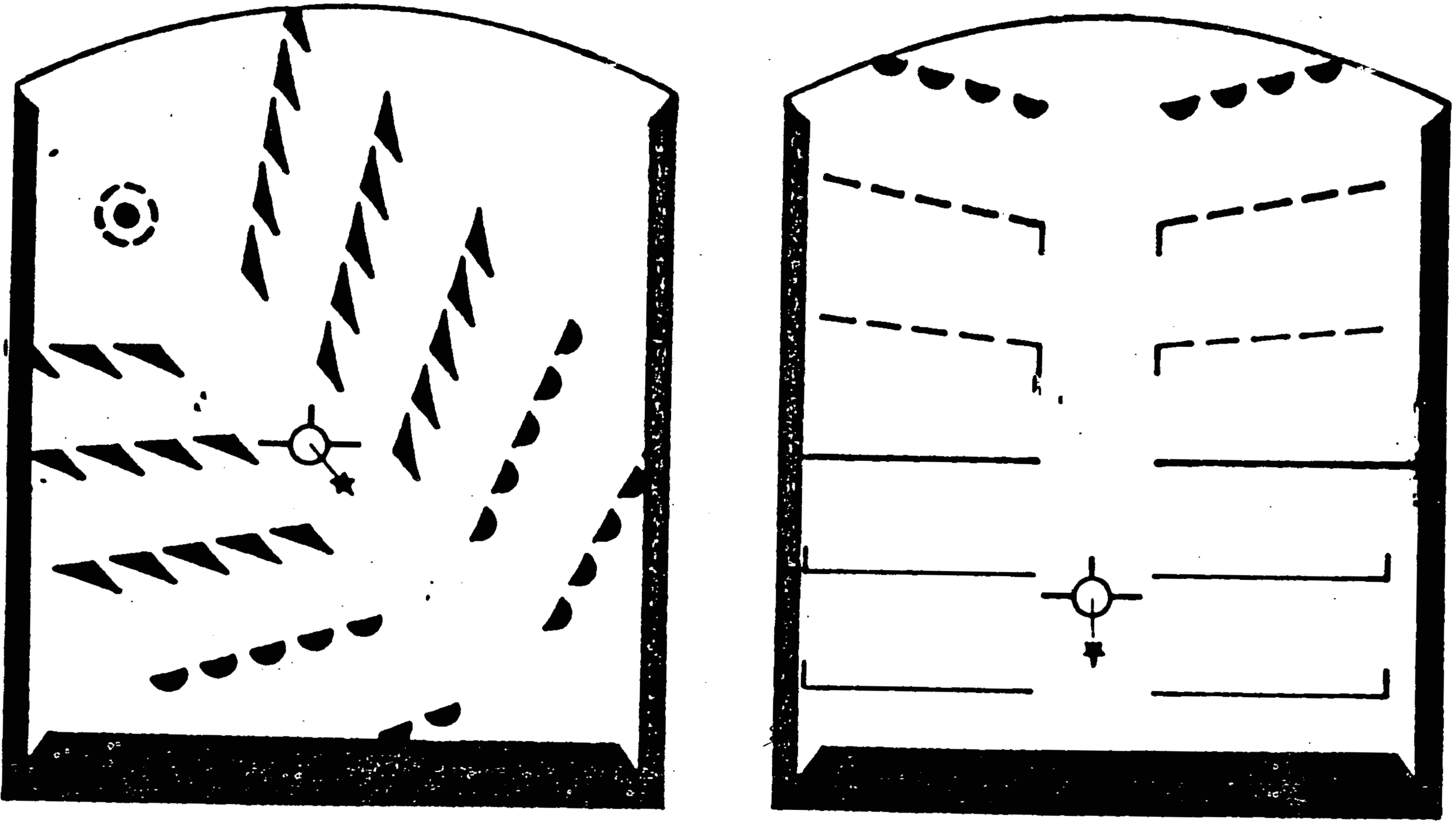
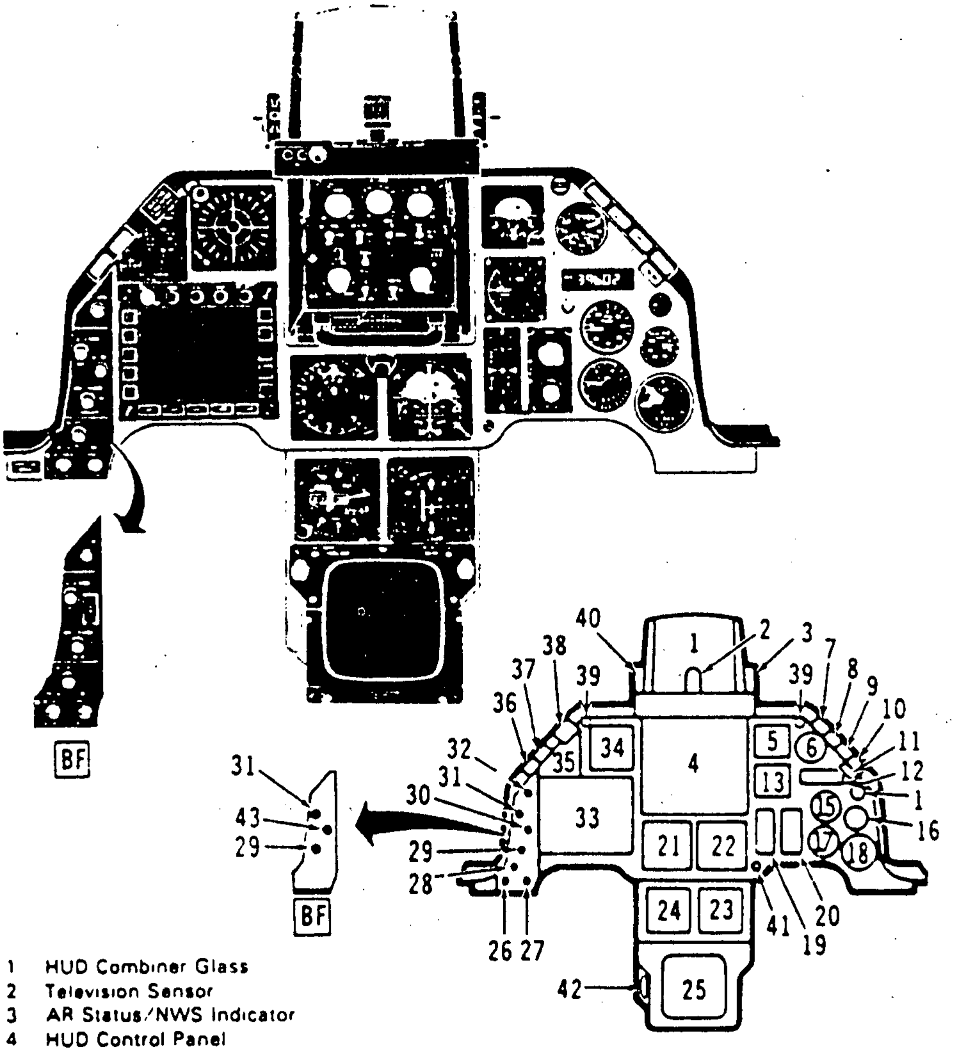


Figure 18

INSTRUMENT PANEL A BF



1 HUD Combiner Glass
2 Television Sensor
3 AR Status/NWS Indicator
4 HUD Control Panel
5. Standby Attitude Indicator
6. Fuel Flow Indicator
7. DUAL FC FAIL Warning Light (Red)
8. HYD/OIL PRESS Warning Light (Red)
9. CANOPY Warning Light (Red)
0. RDR ALT LOW Warning Light (Red)
1. ENGINE Warning Light (Red)
2. Radio Channel/Frequency Indicator
3. Vertical Velocity Indicator
4 Oil Pressure Indicator
5. RPM Indicator
6. Nozzle Position Indicator
7. FTIT Indicator
8. Fuel Quantity Indicator
9. AOA Indicator
0. Instrument Mode Select Panel
1. Airspeed Mach Indicator
2. Attitude Director Indicator
3. Horizontal Situation Indicator
4. Altimeter

25. Radar/EO Display
26. Autopilot PITCH Switch
27. Autopilot ROLL Switch
28. AUTOPILOT Switch
29. MASTER ARM Switch
30. ALT REL Button
31. LASER ARM Switch
32. IFF IDENT Button
33. Stores Control Panel
34. Threat Warning Azimuth Indicator
35. THREAT WARNING Controls and Indicators
36. ENG FIRE Warning Light (Red)
37. T.O./LAND CONFIG Warning Light (Red)
38. MASTER CAUTION Light (Amber)
39. Spotlight
40. AOA Indexer
41. MRK BCN Light
42. Rudder PEDAL ADJ Knob
43. BF OVRD Light

Figure 19: F-16 Instrument Panel, Block 15 Aircraft

aircraft, so was under some self-imposed pressure to get the talley. When it was his turn to be the interceptor, he thought he saw his target, called "Talley", lost talley, then called "Talley" again from a position where he was belly up to his target aircraft--no way could he have seen it. Over the ensuing 1-1/2 to 2 minutes, he proceeded to lose 11,000 feet, impacting near a lighted train siding. It so happened that a train had passed within several minutes. It's possible that his Doppler locked up the train and that he mistook its light for that of his target. Again, we'll never know. But just suppose that he had decided to check his altitude during that pitch black night (altimeter constitutes a fairly critical instrument on a pitch black night over terrain devoid of height references), and not seen it in the old location, could he have simply deleted it from his cross-check? After all, nothing was alerting him that he was going downhill and he certainly did not want to lose sight of that target again.

Or take another tack and ask, suppose the altimeter (or any of the other critical control parameter instruments) were formatted for instant, unequivocal recognition in such a way that they could be monitored by the ambient mode or via a focal mode snap glance; might pilots be prompted to cross-check them oftener and thus maintain their aircraft attitude/altitude awareness with less effort?

That raises the question: In the Pilot Vehicle Interface, what does the pilot really need to maintain attitude awareness? Attitude cues, airspeed and altitude cues without requiring focal mode to dwell on instruments.

Have we considered adequately how the human perceptual system works or what man needs by providing him a proper mixture of inputs to sensory channels other than the focal visual mode? For example, analog, pattern, pictorial, color, orientation; focal/ambient auditory displays; and tactile/proprioceptive cues. Have we asked whether the aircraft "talks" to the pilot by providing him a proper mix of auditory and kinesthetic cues?

The advantages of providing inputs to sensory routes other than the focal visual mode are that it frees the focal mode for tasks requiring focal mode attention, promotes situational awareness, reduces the propensity for SDO and, if formatted correctly, should reduce workload. Regarding workload, we should recall that, most of the time, when a pilot looks at a display, he wants only to know whether the parameter it represents has changed, and, if so, in which direction, how fast and how much.

Now in keeping with man's pattern recognition abilities, why not design instruments taking advantage of that innate capability and also utilize the moving tape format so popular in the past? The moving tape lends itself well to airspeed and altitude. Note Figure 20, in which the pattern of airspeed changes radically from one range to the next to enable recognition out the corner of the eye, once one learns the pattern. In Figure 21, the altitude is a zig-zag pattern to create a side-to-side motion that might help catch the

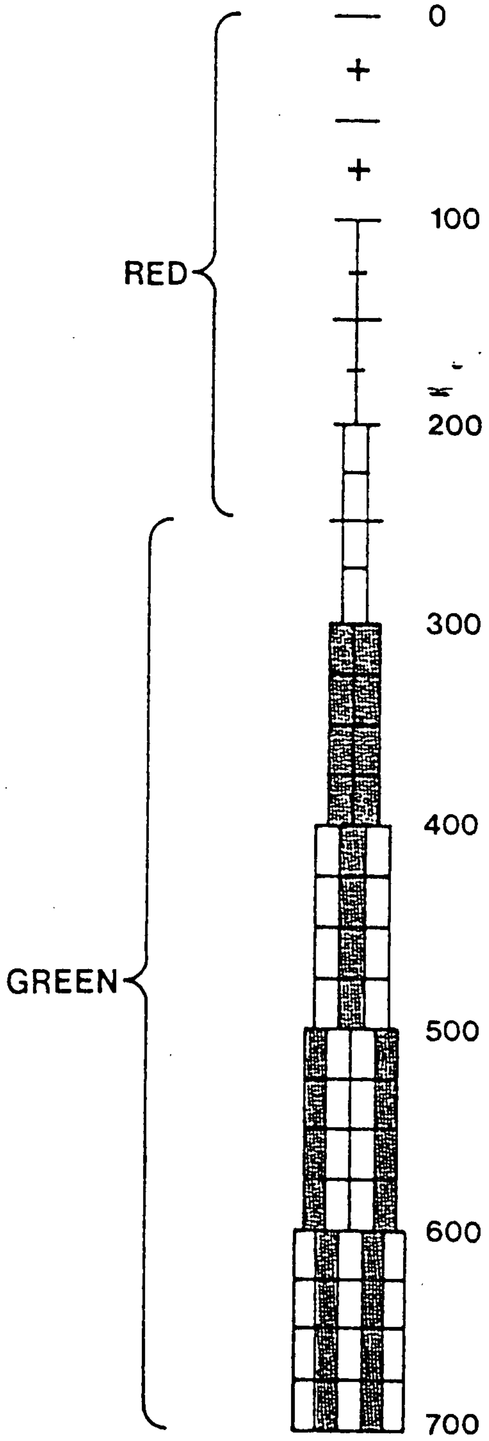


Figure 20: Moving Tape Format Proposed for Airspeed Indication

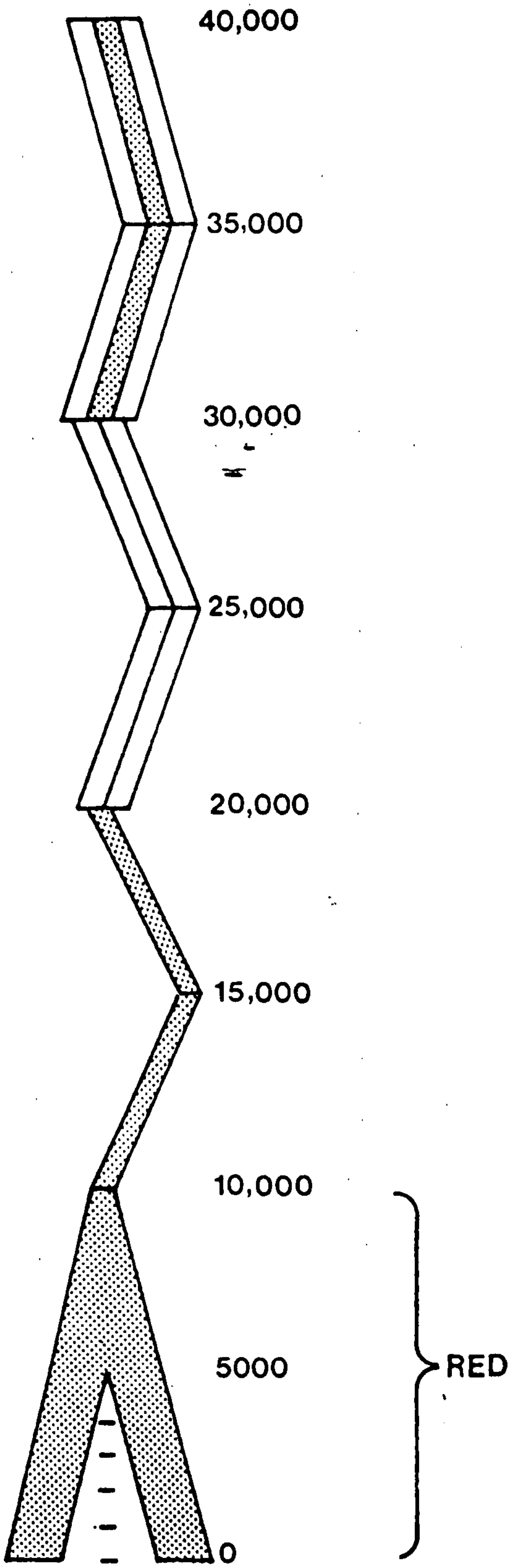


Figure 21: Moving Tape Format Proposed for Altimeter

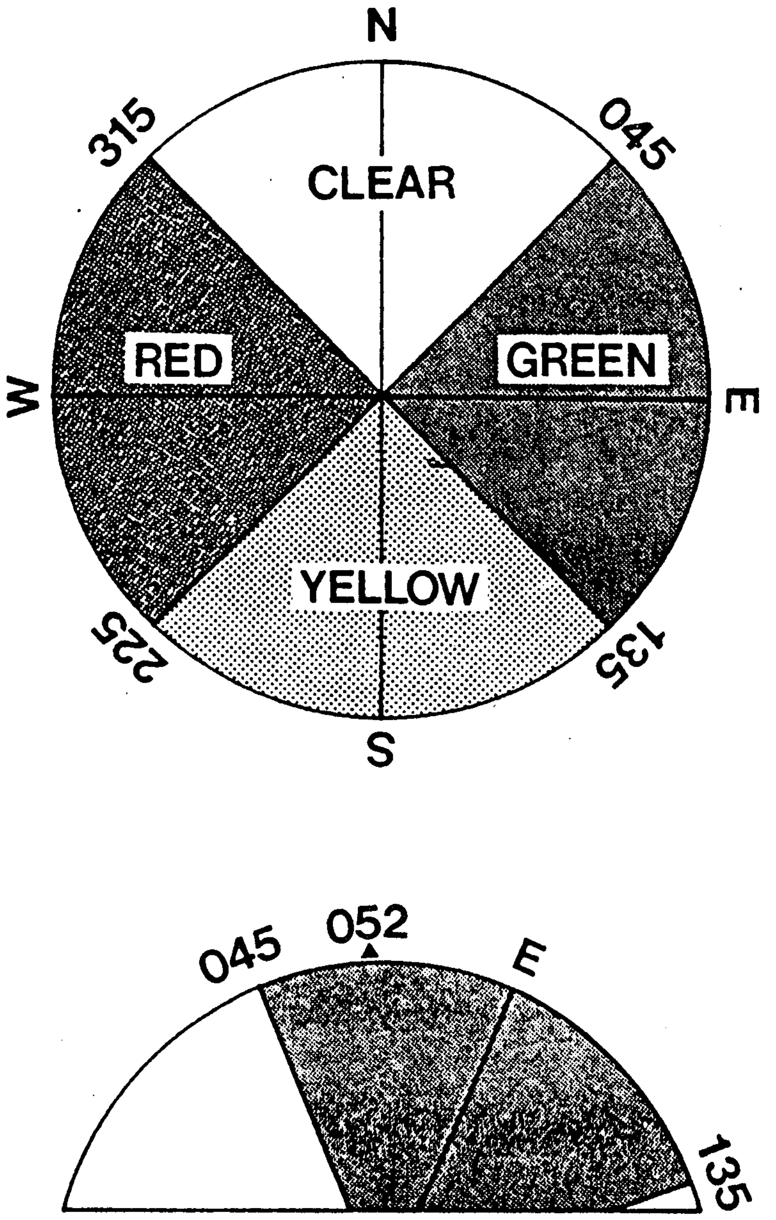


Figure 22: Proposed Heading Indicator

pilot's eye should he enter an unplanned descent with his attention directed elsewhere. The pattern would again change radically below 10,000 feet. The reason for this is that certain out-of-control maneuvers, such as roll rates over 100°/second, can exceed the fixating capacity of the eye, making everything a blur. It would take a big, bold, instantly recognizable pattern change in the altimeter at this point to alert the victim that the time has come to recover the aircraft now or else eject without further delay.

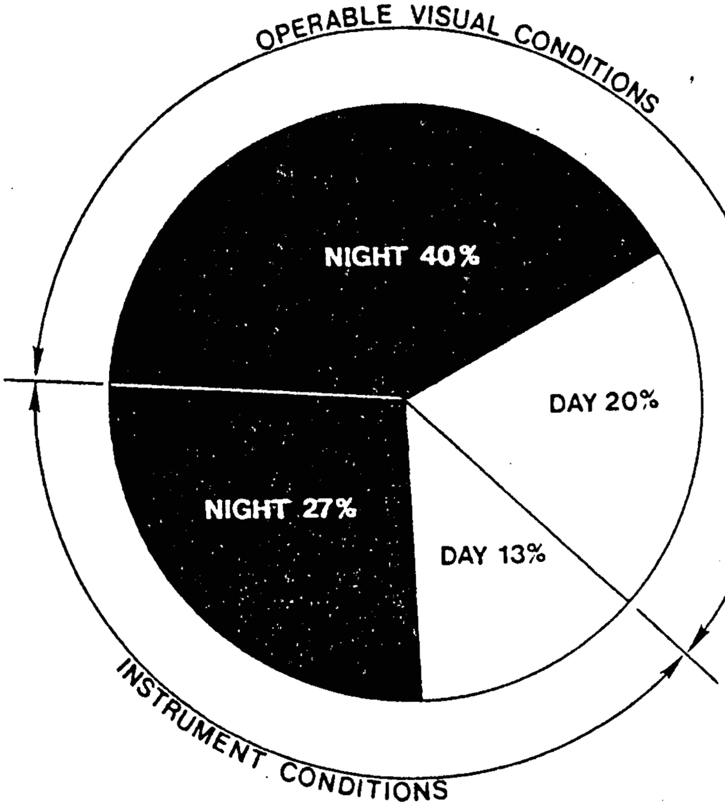
While on the subject of display improvement aimed at reducing processing time and workload, why not use the color pattern recognition capabilities of the ambient mode for heading? As per Figure 22, the entire compass might not need to be shown; perhaps the top one-fourth or one-third would be sufficient.

The night-weather role needs mention again. Regardless of the original intention in procuring the aircraft, if it has AF markings, it will sooner or later be flown at night and in weather. To answer the question of why train in night/weather, one has to look no further than a chart showing the average weather conditions for any typical 24-hour period during the winter in central Europe (Figure 23). This pie-graph shows that about 40% can be expected to be IMC. The reason we train night/weather is that we may very well have to fight there.

The night role requires some special considerations. For the pilot, fatigue is a given; reactions are slowed; perceptions impaired--especially height and distance judgments; and he is more subject to illusions, disorientation, distraction and channelized attention.

The aircraft needs special considerations, too. No longer is it permissible to say, "It's a day VFR air superiority dog fighter," and wash our hands of it. That type of attitude constitutes negligence. For the night role, aircraft need, as a minimum:

- Better attitude references to include a large, primary dedicated attitude display (PDAD) high in the center of the instrument panel.
- Critical control parameters formatted for instant, unequivocal recognition.
- Better cockpit/instrument lighting with minimal, if any, canopy glare and reflections.
- Better formation lighting.
- No false horizons from external lighting.



FLYING CONDITIONS - CENTRAL EUROPE
WINTER - TYPICAL 24 HR. PERIOD

Figure 23: Pie graph showing the average weather conditions during a typical 24 hour period in Central Europe during the Winter

Well, with all that, just where are we headed in the design of the modern cockpit? Note the F-15E and F-18 (Figures 24 and 25). No dedicated primary ADI (it's on call on any of the multi-function displays but it is not there all the time--which means that it is not there to alert the pilot that he needs it). Each has an SAI, low in the instrument panel and effectively out of view. On the F-16C/D, Figure 26, note that the primary ADI has been moved even deeper than in the A/B, to a sort of "Y" cross-check pattern. Note, also, all that prime real estate occupied by the HUD control panel. As an improvement, why not use that area for a primary attitude display, as per Figure 27, so that it displays attitude practically within the same field of view as the HUD?

If we do not set our priorities properly in the design of future aircraft, we're going to lose many of these ultra-expensive machines, and their pilots, in training mishaps. The first priority is aircraft control--and the ingredients of good aircraft control are an awareness of attitude, airspeed and altitude. Attitude control is basically a visual task. To improve attitude control requires improved visual displays, as we have attempted to illustrate. But that's not the whole problem.

Just as important is altitude awareness--loss of altitude awareness results in collisions with the ground, the controlled flight-into-terrain (CFIT) mishap. Currently, CFITs outnumber SDO mishaps 2 or 3 to 1 (Figure 28). CFITs account for the largest proportion of operator error mishaps and fatalities. To attack this problem, we cannot rely on vision. This is basically a problem of alerting the pilot, whose attention is invariably directed elsewhere, to check his flight path and pull up. What he needs are audio warnings and alerts; effective, unequivocal inputs to his hearing system. You'll hear more about this in the days ahead.

Finally, if all else fails, if the pilot is incapacitated, either physically, as in G-induced loss of consciousness or hypoxia, psychologically, as in severe disorientation/vertigo, or visually, as in laser/nuclear flashblindness, the aircraft should resist crashing and recover itself. The state-of-the-art is rapidly approaching the point of being able to do this, and we are approaching the point of building aircraft that are simply irreplaceable, dollar-wise, not to mention their occupants. You'll hear more about aircraft that resist crashing and auto-recovery on Thursday.

F-15E Forward Cockpit

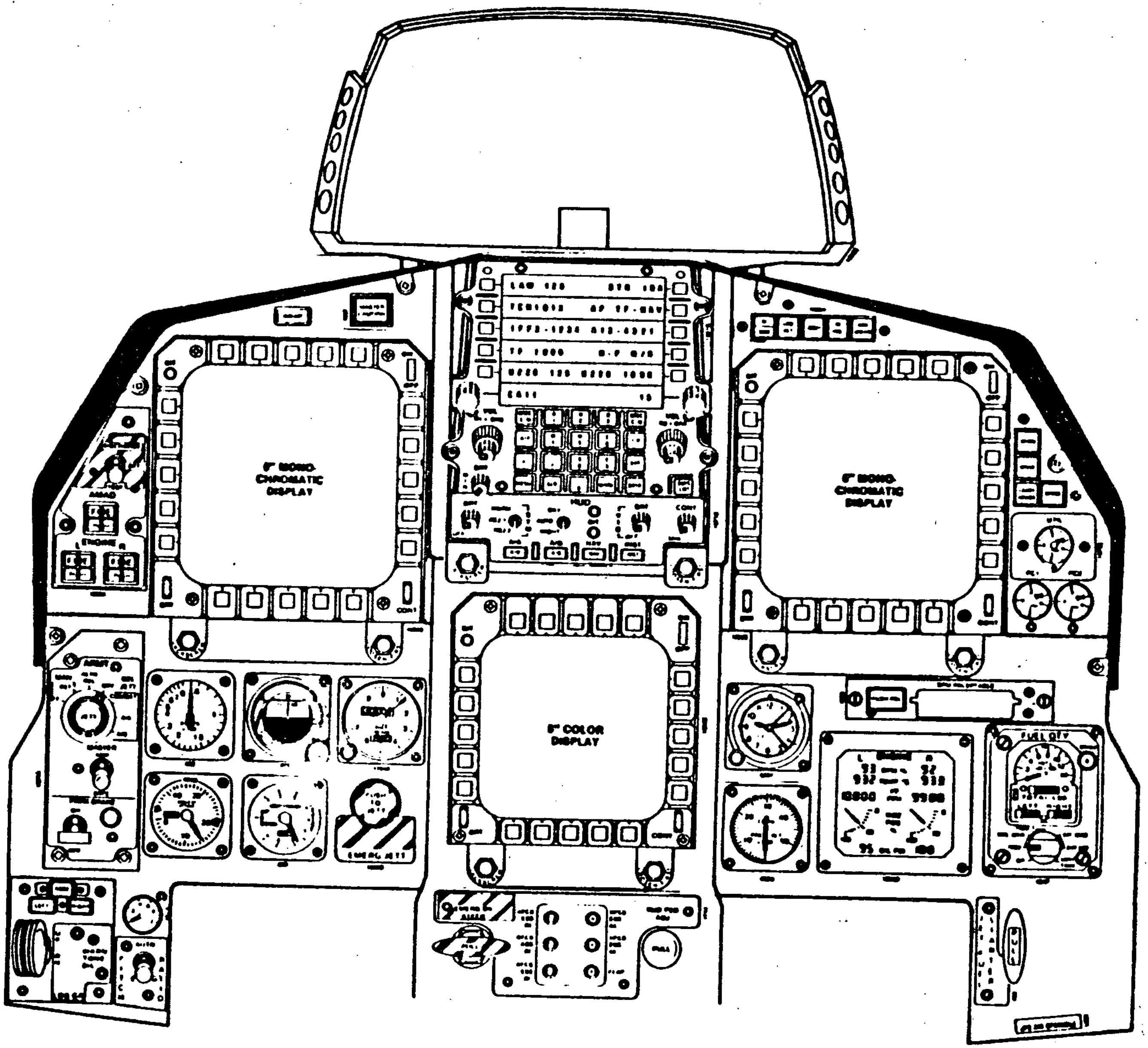


Figure 24

F/A-18 HORNET COCKPIT

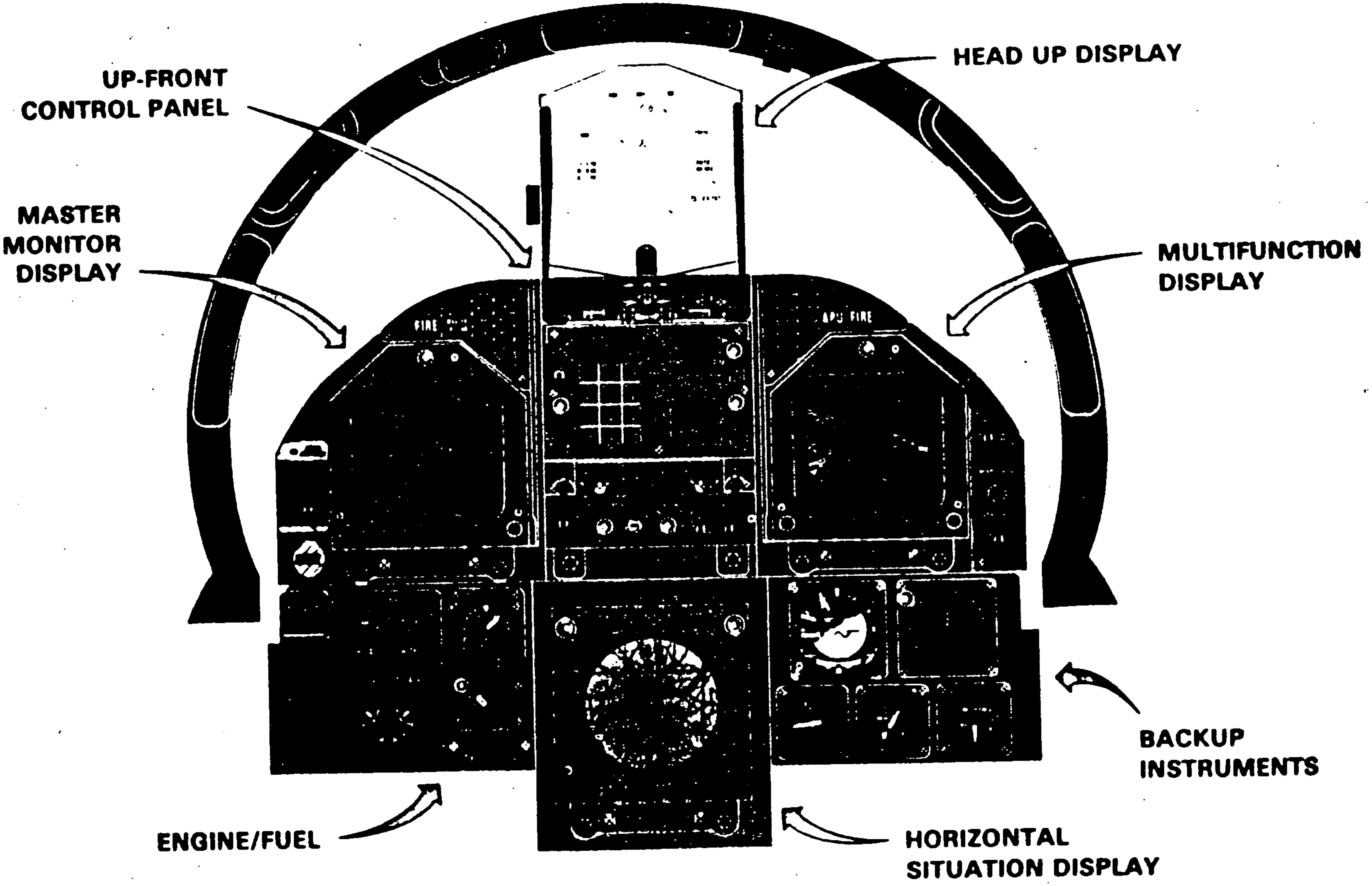
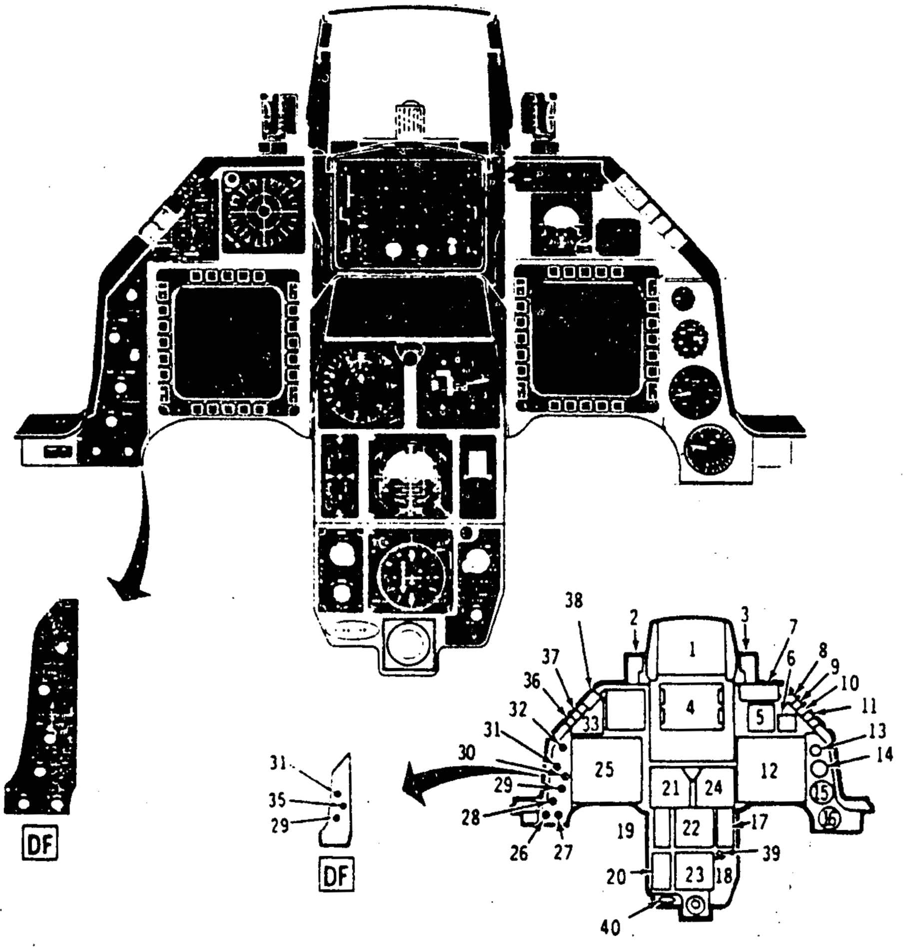


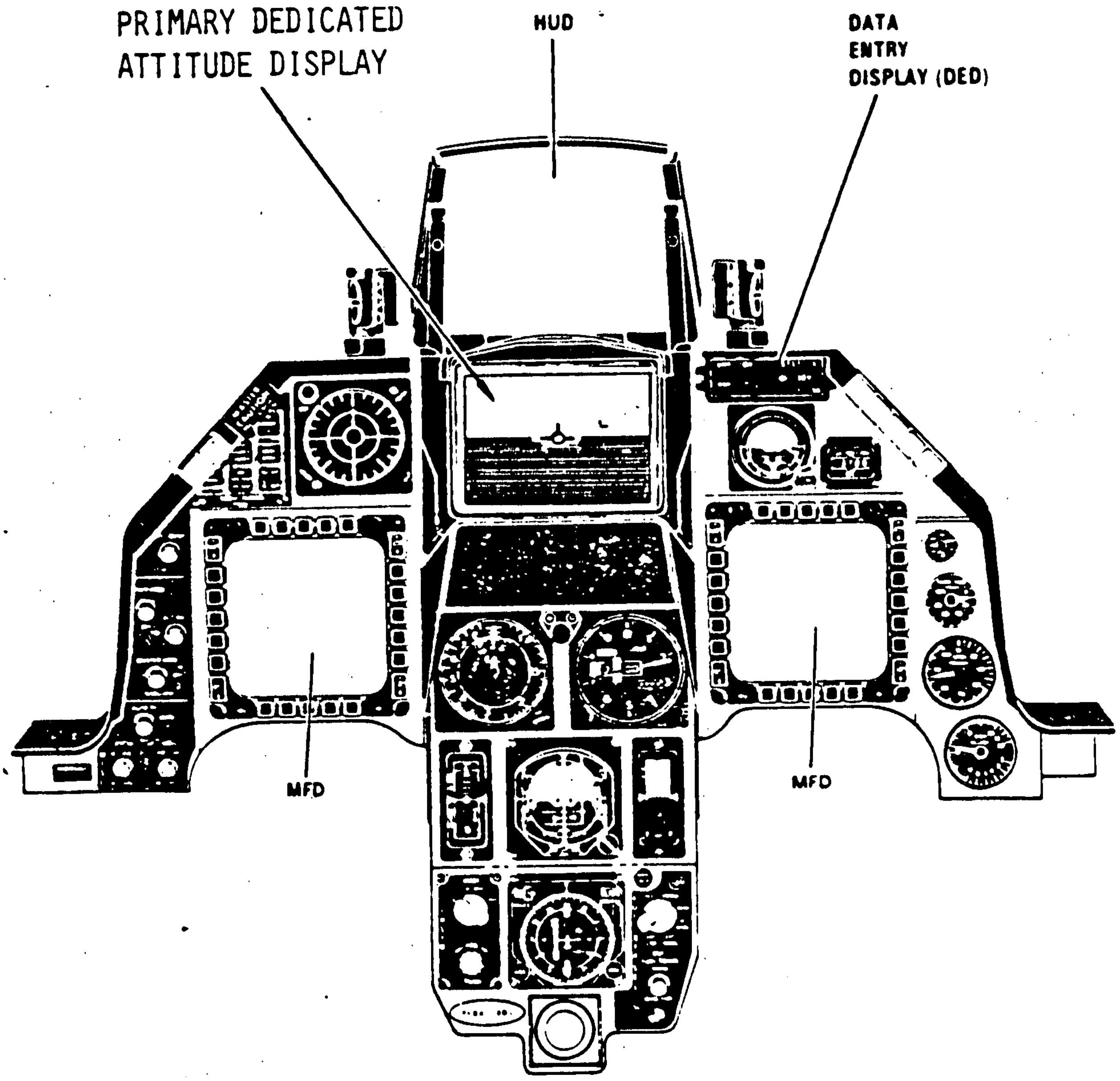
Figure 25

INSTRUMENT PANEL C DF



1 HUD Combiner Glass
2 AOA Indexer
3 AR Status/NWS Indicator
4 Integrated Control Panel
5 Standby Attitude Indicator
6 Fuel Flow Indicator
7 Data Entry Display
8 ENG FIRE and ENGINE Warning Light (Red)
9 HYD/OIL PRESS Warning Light (Red)
10 DUAL FC and CANOPY Warning Light (Red)
11 T.O./LAND CONFIG Warning Light (Red)
12 Right MFD
13 Oil Pressure Indicator
14 Nozzle Position Indicator
15 RPM Indicator
16 FTIT Indicator
17 Vertical Velocity Indicator
18 FUEL QTY SEL Panel
19 AOA Indicator
20 Instrument Mode Select Panel
21 Airspeed Mach Indicator
22 Attitude Director Indicator
23 Horizontal Situation Indicator
24. Altimeter
25. Left MFD
26 Autopilot PITCH Switch
27. Autopilot ROLL Switch
28. TF Switch
29 MASTER ARM Switch
30. ALT REL Button
31. LASER ARM Switch
32. IFF IDENT Button
33. THREAT WARNING Controls and Indicators
34. Threat Warning Azimuth Indicator
35. DF OVRD Light
36. TF FAIL and OBS WRN Warning Light (Red)
37. ALT LOW Warning Light (Red)
38. MASTER CAUTION Light (Amber)
39 MRK BCN Light
40 Rudder PEDAL ADJ Knob

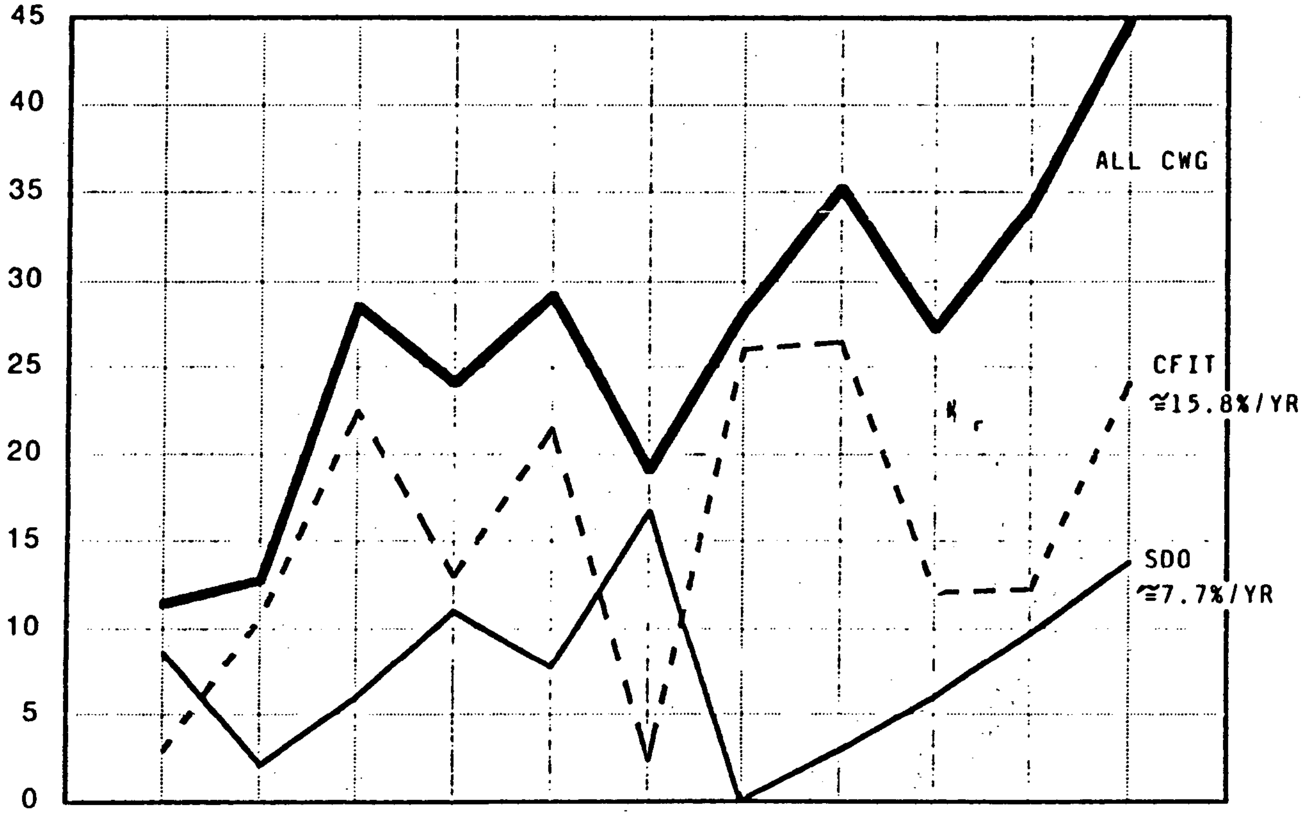
Figure 26: C/D Instrument Panel



C DF

Figure 27

COLLISIONS WITH GROUND - % OF OPS CLASS A MISHAPS
1 JAN '75 - 4 OCT '85 (AFISC)



	75	76	77	78	79	80	81	82	83	84	85
CWG	11.4	12.8	28.6	24.1	29.2	19.1	28.3	35.3	27.3	34.2	44.9
CFIT %	2.9	10.6	22.5	13.0	21.5	2.4	26.1	26.3	12.1	12.2	24.1
SDO	8.6	2.1	6.1	11.1	7.7	16.7	0	2.9	6.1	9.8	13.8

Figure 28: CFIT vs SDO Mishap Chart

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SPATIAL DISORIENTATION IN THE F-15

Major Merrill Beyer
Tactical Air Command, ASD/TACSO-A
Wright-Patterson AFB, Ohio

BIOGRAPHY

Major Beyer graduated from the Air Force Academy in 1974, majoring in Aeronautical Engineering. After UPT at Webb AFB, Texas, he flew F-4's, then had an OV-10 tour in Korea. He then flew the F-15, accumulating 100 hours in all models in PACAF, USAFE and TAC. His total flying time is 2500 hours.

Major Beyer served as investigating officer on Col. Kehoe's spatial disorientation incident, the video tape of which introduces this conference. Major Beyer's current position is Tactical Air Command Systems Officer, Wright Patterson AFB.

The opening photo depicts an F-15 firing an AIM-7F during an air-to-air engagement; it also shows the clouds with potential for a spatially disorienting environment. This represents but one example of the kind of weather in which an Eagle pilot must operate.

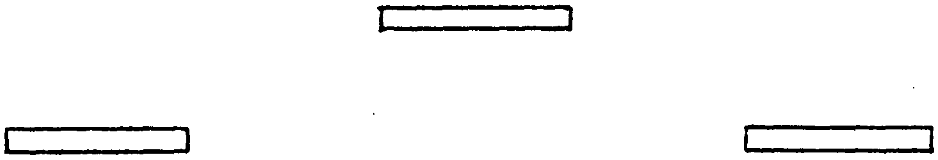
Today, I'll discuss the attitude awareness problems that have been experienced in the F-15 and then relate these problem areas to three operating environments. A primary concern is spatial disorientation (SDO) during air-to-air employment.

The Directorate of Equipment Engineering commissioned a study entitled "Investigation of Spatial Disorientation of F-15 Eagle Pilots," which produced Technical Report ASD-TR-81-5016, released August 1981. Although this document is four years old, it remains the authoritative source on the subject. This TR concluded that the following are not major factors that contribute to SDO:

- Flight handling characteristics
- Bubble canopy
- Sitting height
- Cockpit design - the cockpit, in particular, is designed to minimize head movements and provide easy access to the most commonly used items: UHF and IFF.

On the other hand, these are the factors that do contribute to SDO:

Formation strip light asymmetry -



As can be seen from the diagram, the pilot must maintain his formation position by using an unnatural sight picture. Whenever the wingman sees the lights lined up, he is either flying dangerously high on lead's wing, or, worse yet, he discovers that lead has rolled into him. Because of this, wingmen tend to fly further out to maintain a safety margin. Several suggestions for improvement included vertical strip lights on leading edges of the tails to enhance detection of lead's attitude and closure rates, and installation of a shielded light in the wings to illuminate the fuselage.

- Tail lighting - due to vibration, this is often inoperative, making stern rejoins at night and discernment of bank angle difficult.

- HUD - though a tremendous aid to precise instrument flying, the night brightness is difficult to control. One cannot see night targets when symbols are bright enough to be used. Effectiveness of the HUD as an attitude display will be discussed later.

- The Air-to-Air Environment - a problem area not discussed in this study is SDO in the day-visual air-to-air environment. Shortly, we'll review a videotape of a recent incident and analyze this area in more detail.

Spatial Disorientation Environments: We can group these problem areas according to the method by which a pilot maintains his spatial orientation:

- Instruments only
- Instruments and visual references are used together
- Primarily visual
- Formation flying - a special case, actually a subset of each of the above 3.

Instruments Only (IMC - Day or Night): In this group, mishap experience in the Eagle has involved the following two operations. Each case involved a pilot unable to recover from an unusual attitude brought about by his SDO.

- Radar trail departure
- Lost wingman

Instruments and Visual References (Partial IMC/VMC - Day or Night): In the partial IMC/VMC environment, the problem these mishap pilots most likely encountered was futile attempts to maintain spatial orientation by use of inadequate visual references. They delayed too long before "going to the gauges."

- Night formation
- Attempting to maintain VFR at low altitude

Primarily Visual References (Day VFR - Tactical Employment): This last group has had the least amount of attention. It is manifested on the gunnery range, for example, when an F-4 pilot looks over his shoulder to watch his bombs impact the target and flies his aircraft into the ground. It occurs frequently in the F-15 during air-to-air engagements over water.

AFM 51-37, Chapter 7 (Spatial Disorientation), states that, "On a clear day, spatial disorientation simply does not happen." To illustrate the error in this statement, lets roll the video (VTR of Col Nicholas B. Kehoe, 1 TFW/DO, Langley AFB, VA, Feb 1985. For narrative, please see 1-5.)

Air-to-Air Employment and SD: Let's examine what factors are at work that enable a pilot to become disoriented when plenty of visual references are available.

- False vestibular perceptions vs visual dominance - one factor that can be ruled out almost immediately is false vestibular perceptions. Visual dominance is just too overpowering.

- Nature of aerial combat - To understand the problem, we must examine the very nature of aerial combat.

  - A pilot's brain is like a high speed computer, constantly integrating three frames of reference: the earth's surface, the bandit's flight path, and his own. To bring ordnance to bear, he must maneuver in relation to the bandit. This is drilled in repeatedly during Lead-In-Fighter Training.

  - Also, a fighter pilot's mindset is based on the admonition that "to lose sight is to lose fight." He's going to padlock his attention on that bandit, which then becomes his sole frame of reference. Flying the aircraft and avoiding the ground are still "first priorities" - but they often drop out in the heat of the fight.

- Fighter pilots are extremely competitive--keeping sight of and maneuvering in relation to the <u>Bandit</u> quickly become his top priorities. When I say that fighter pilots are competitive, I don't mean to say they are undesciplined. This incident happened to the Wg DO at Langley - a highly responsible full Colonel, not the kind of guy who would be out there shining his rear end.

- Consequently, the cues that Eagle pilots use for spatial orientation during aerial combat are:

-- Bandit
-- Wingman
-- Horizon: Over water, through the horizon may register such as, it doesn't tell which way is up.
-- Ground references
-- Sun
-- Clouds

Order of importance of the instruments:

The <u>altimeter</u> is probably used the most, followed by the <u>HSI</u>, the <u>fuel gauge</u>, and the <u>rounds count</u>. Note the HUD is not in there, except for the target display. If the target is in the HUD FOV, he'll look at the HUD, but the pitch scale usually doesn't register: many pilots declutter the attitude reference symbols, rejecting them anyway.

HUD Deficiencies:

o Attitude awareness
o Recovery capability
o Failure warnings

The attitude presentation of the current HUD does not lend itself to easy attitude interpretations--Col Kehoe looked into the HUD, "and it didn't register." The instant he saw the ADI, he knew exactly <u>where</u> he was and <u>what</u> he had to do. Recognition was instant via the ADI; so was recovery.

HUD Picture: This picture of a typical HUD display looks fine on paper, but proves confusing and inadequate in the air. Note that everything can be rejected (decluttered) except the Target Designator box and Aiming Reticle. Even the FPM (of Velocity Vector) can be rejected in the Air-to Air Mode. (Ed. Note: All the more reason for a Primary Dedicated Attitude Display right below the HUD.)

Coupled with the shifted set of priorities during air-to-air comes the problems encountered in over-water airspace: put these all together and you have the perfect set up for SDO. Happened a lot at Kadena.

- Blue sky/blue water
- Unstructured field - no discernable landmarks; denies the eyes anything on which to focus.
- Complacency - a problem on CAVU days: when you're flying in IMC or off the tanker, you expect SDO, so you are mentally prepared and alert for it and keyed to it. That's not so when it's clear and a million and you think you have all those visual references immediately available. You're not as keyed.

Conclusions:

- Spatial disorientation in general: How do we solve this problem in the F-15?
    - Stress importance of ADI use
    - Practice HUD-out approaches, especially for the new guys who grew up in that simulator environment, and their assignment is the first time they see a cloud.
    - Lost-wingman procedures; once lead has disappeared, don't hesitate to get on the gauges and go lost-wingman, and for lead to supply critical information like heading, attitude, and airspeed.
    - Radar trail procedures hammer into them: fly the aircraft! First priority is to fly the aircraft, second, fly the SID, then last try to get a radar contact on the Leader.
- Spatial disorientation during air-to-air
    - ADI cross-check still important: even though it's DAY VFR, guys are now aware of the fact that this can happen to them and they still have to look at the ADI.
    - Rewrite applicable portions of AFM 51-37 to provide pilots an authoritative source.
    - Along with that, move to incorporate vertifuge training with visual displays.

That concludes my briefing. Thank you.

AIRCRAFT ATTITUDE AWARENESS WORKSHOP
8-10 October 1985

Colonel Kehoe's Spatial Disorientation (SDO) Incident In an F-15 During VMC

Narrator: Col Nicholas B. Kehoe, 1 TFW/DO, Langley AFB, VA

This tape transcription depicts at least the third such episode involving SDO in an F-15 during VMC. All occurred during ACM over water. One involved an F-15 aircraft operating over the ACMI range at Decimomannu. Another, an F-15 aircraft operating over Lake Michigan. In this second instance, the sky was a milk-bowl with blending of sky and sea and no good discernible horizon. At the Knock-It-Off point, the F-15 pilot thought he was heading uphill, so he simply let go of the stick expecting to coast over the top. At that point, he looked up through the top of the canopy and saw the shoreline. His initial impression was that he was in an inverted climb, but then it occurred to him he might be in an upright dive. He immediately checked the ADI and saw all black. He pulled over 11 G's and missed the water by very little--way less than 2000 feet, according to my source, Col (Dr) Leroy Gross (former F-15 pilot-physician).

Col Kehoe's incident occurred on a clear day with unlimited visibility and good sea-sky contrast, and a distinct horizon. Through Col Kehoe does a highly professional job of narrating this episode, he does not say on the tape what it was that alerted him that something was wrong. In a telephone conversation with him, he explained that what alerted him was a noise cue. The aircraft sounded like it was going fast. (And sure enough, it was over the Mach). I think that's an important point to bear in mind--an auditory cue to airspeed helped save Col Kehoe. Later on, you'll hear about another of our state-of-the-art single-seat fighters that lacks auditory cues to airspeed, the F-16, which sounds the same whether going fast or slow, with implications for attitude awareness.

Now for the transcription of Col Kehoe's VTR.

I'm Col Nick Kehoe, Deputy Commander for Operations of the 1st TFW, Langley AFB, VA. I'd like to take a few minutes of your time to narrate an incident that occurred a few days ago. Over the past few years, the TAF have lost several pilots and aircraft for unexplained causes. We've attributed those losses to GLC or in some cases to SDO, but we never really knew for sure because those pilots aren't around to tell us what went wrong. I'm one of the fortunate ones who is here and able to tell my story, and you're fortunate too in being able to listen to this story so you'll have something to stick in your warehouse of knowledge, so maybe it won't some day happen to you.

Before getting into the details, I'd like to show you a short piece of VTR from the flight just to set the scene, and watch for a couple of things.

First, as the merge occurs, watch the angles of bank, first a roll to 90° right, followed by a roll all the way back to 135° left, a short roll out to 90° left, followed by a roll to the inverted position very nose low, followed by the unusual attitude recovery.

Second, watch how fast things occurred once that nose got down well below the horizon. That unusual attitude took only a few seconds to develop. By the way, the weather was clear and there were no restrictions to visibility.

All right, here goes. (Runs tape showing development of the inverted dive and the dramatic recovery.) Get your attention? Needless to say, it got mine. What went wrong here?

The mission was a 2V2 CAP V sweep with me giving a flight lead upgrade ride. We're the good guys, call sign Lion, and the other element, Wolf, is simulating Soviet tactics; Wolf's heading south and they're in a bearing formation to the northeast. They're the high element and their right hand man is high.

Lion is flying north in a two mile split and we've offset our adversaries to the right. We're the low element and I'm on the left hand side. Okay, let's take things up to the merge. (Plays VTR again while narrating it.) Note just inside ten miles my radar goes into Home-On-Jam, then memory, then breaks lock. I reacquire lock and quickly get a tally on one above me, slightly right. So I reach the merge, tally one, with my threat and flight lead off to my right. Next I roll right to acquire the second adversary who I know is in a bearing formation to the NE. I think I've rolled maybe 30° where the VTR shows 90°. That's the first clue that something's wrong. I miss it. At that time, Lion one calls for a blow through to a 030° heading. I check my heading, my fuel, and call joker, then look for the second adversary. Notably I don't check my attitude inside or outside. Now I roll to what I think is wings level. The VTR shows a roll from 90° right, all the way to 135° of left bank. I then roll out to about 90° of left bank. Remember, only a few seconds have elapsed. It is at that time that I pick up the second bandit over my canopy rail at about one to two o'clock. Note that when I'm in that 90° of left bank, I think I'm straight and level. So while I think I'm looking over my canopy rail down at the bandit off my nose to the right, I'm actually looking up at the bandit. Better situational awareness would have told me that. My next intended move is to check left and pull my nose up slightly. What I actually do is roll from 90° to near inverted and pull my nose down. It's very quickly after that that I realize something is wrong. I'm now inverted, 60-70° nose low and over the Mach. I look outside for an attitude reference, but it doesn't register.

Let me tell you, from an inverted 60-70° dive, it's difficult to get your bearings, particularly when your gyros are already off track. Anyway, I immediately come back inside to the ADI and see black. From there, it was all instinct; roll to the horizon and pull for all you're worth, with both hands, as it turns out. I also wound up doubled over the stick and looking at the floor. That's just great when you're trying to recover from an inverted 60-70° dive, and aren't sure how far you need to roll and pull. The aircraft bottomed out at 2000 feet. But that's not all. As my nose comes through the horizon, I'm still rolling left. I've taken my right hand and put it on the right console to push myself up off the floor. My left hand is on the stick. As I get to where I can see the ADI, which is the only thing I'm interested in at that point, I'm slicing through the horizon again.

What happened is I bottomed at 2000 feet, came up through the horizon in a rolling left bank, topping at 3000 ft then sliced back down through 2000 ft before making the final recovery.

All right, let me show it all the way through again one final time. (Note the time from first rolling inverted to realizing something was wrong was about 4-6 seconds, and from then to full recovery another 18-20 seconds.)

So, why did it happen? One of the basic tools in a fighter pilot's tool bag is a good cross-check, IMC, VMC, day or night. How many times have you heard that? I dropped that tool out of my bag on this engagement and it almost cost me. I violated one of the fundamental principles of single seat flying. I got caught up in keeping track of everyone at the merge except one, and that's me. I overlooked the number one priority: What was my airplane doing? That's the bottom line. We've learned that time and again. And I did that in an airplane that doesn't give you as much outside sensory cues, as much feel if you will, as did the F-4. And I understand the F-16 is even more that way. So what do we learn from an incident like this?

First, it can happen to anyone at anytime. I have over 3000 hours in fighter type aircraft and have flown in virtually every conceivable environment. I've had vertigo before, but I never thought anything like this could happen to me.

Second, the environment. It was a clear day, virtually no haze. We talk a lot about the over water sea-sky contrast, and it's a good thing we do because it's different. When I was nose low, inverted and over the Mach, it didn't register. Luckily, the ADI did. At Langley we put a lot of emphasis on the danger of frequent over water air-to-air training.

Third, procedures--you know, those unusual attitudes you've practiced over the years. It's important your reactions be instinctive. Someone told me after the flight that if I had delayed by two seconds--just two seconds--I wouldn't have had enough altitude to recover. That's not much margin for error. It happens fast, real fast. I was also asked if I believed the ADI.

You bet I did, just like the book calls for in an unusual attitude recovery. It had a lot higher reliability than my vestibular canals.

Finally, one thing we might not normally think about: after-effects. After I recovered and was headed home, I found it very hard to concentrate. I essentially did everything correctly, but I found it real hard to do it. I decided to take the lead and have my wingman keep a close eye on me. Whether it was the adrenalin, the effects of the G's or the disorientation, I don't know. The point is, it's important to realize that when a flight member has a serious incident, don't assume everything's okay just because you're straight and level and headed home. It doesn't end till the flight's on the ground.

One more thing that's inevitably asked is the effects of the G's. I pulled nearly 12.5 G's in recovering that aircraft, and I've been asked whether I blacked out. As far as I know, I didn't. Remember I was bent over the stick with my head below my heart, and I can distinctly remember looking at the floor and putting my right hand on the console to push myself up.

I don't recommend that as a GLC avoidance maneuver, but maybe that plus the adrenalin made a difference. The reason I mention it is I wouldn't want anyone to get the idea that you can beat the G's. I certainly don't think I'd win that battle in the normal day to day business.

Well, that's my story. I tell it in the hope that you'll add one more bit of reinforcement to your fighter-pilot's tool bag. I know I've learned a lesson and I hope you have, too. Check six, but don't forget to check your nose position, too. Head's up.

PILOT'S VERTIGO AND ATTITUDE AWARENESS IN THE A-7D

Captain David H. "Zack" Zayachkowski
Louisa Station, Santurci, Puerto Rico

BIOGRAPHY

Certificates and education: Commercial Rating; Multi-Engine Land; Instrument Rating; Single-Engine Land; M.A. - Human Relations and Management, Webster College, 1979; B.S. - Biology, Eastern Michigan University, 1971; Qualified - Investigator, Safety Investigation School, USAF, 1978; Squadron Officers School, USAF, 1976.

Aircraft experience: B-707/720, DC-3, A-7D Attack Fighter, T-37/T-38 Trainers, Light Aircraft.

Flight time: 2,768 Total, 1,833 PIC, 1,335 PIC (Jet), 2,023 Multi-Engine, 1,500 Cross-Country, 702 Instrument, 290 Night.

Military Airlift Experience: May, 1971 to January, 1981. As a Pilot and Co-Pilot in Command, experienced in flights involving cargo and passenger transport throughout the United States and overseas. Operated under all types of adverse weather conditions at airfields ranging from major international aerodromes with high density traffic to small, isolated airports having limited navigational aids.

Aviation Management Experience: Directly supervised eleven personnel as Airfield Manager monitoring all aspects of aerodrome maintenance and operation. For a period of two years, acted as Safety Officer conducting on-site investigations of accidents to determine extent, cause and responsibility. As Officer Controller from 1974 to 1976, in charge of all flying as well as non-flying activities throughout an entire air base with a personnel involvement of approximately 2,000.

USAF Flight Instructor: Responsible for Flight Instruction at all levels to include: new pilot training, instructor training and up-grade training - both U.S. Military and Foreign Nationals.

Civilian Experience: Previous experience encompassed Contractual Maintenance and Service Vice President for Zelda Elevator Company; insurance sales for Wisconsin National Life Insurance Company; insurance investigation for Equitable Life Assurance Society of America.

The A-7D was designed in the 1960's. The A-7 was the first aircraft with a HUD that caused problems for pilots geared to the old "T" and ADI hub. Need to move the stick to see the HSI. SAI impossible to see from high seated position. Vertigo traps to sides: TACAN, ILS. There are too many switches; they say, "It's just another switch, but there are already so many of them.

Sit high - canopy rail low. Susceptible to canopy glare and reflections at night. Flying around Puerto Rico at night causes canopy glare and reflections. Lighting barely adequate; instruments cluttered - out of view - poorly lit.

First HUD system: I use it for limited functions: bombing and air combat maneuvers (ACM) - not for instruments. When flying in clouds or with a x-wind, the flight path marker (FPM) slews out of view leading to spatial disorientation (SDO). HUD is not recommended for IMC. ADI is the primary instrument.

Day IMC has led to SDO; a flight lead got it while flying off the HUD. He flew into a cloud and attained 135° left bank and 20° ND before realizing anything unusual.

Wingman: worst position - especially being #4 at night; therefore, we fly only two ships. The formation lights are not adequate, especially if they're not working. Even working properly, they only light up the aft 2/3 of the ship, making it appear as though the aircraft is farther away than actual. No way to teach vertigo coping to a wingman except do it.

Automatic Flight Control System (AFCS) malfunctioning: HUD tied to the system; you should never, never land. Must first turn it off or it becomes a B-52. Tough enough to fly VFR - night IMC impossible.

Speed brake - 10' long - stops aircraft on a dime; produces a Coriolis effect at night or in the weather.

Low Level Bombing - line abreast: at 540 kts, a 1° descent from 50 feet AGL provides only 3 seconds Time to Impact (TTI).

Smudge pot flares at night: leads to Star Wars Effect (SWE) on night ground attack - especially pulling off the target; going from lighted terrain and sky to pitch black produces the SWE and SDO.

Fog - all factors - night ground awareness. Need to watch altitude and stay on instruments.

Night rejoin - lost #4 on normal/normal night rejoin following some range work. Lost SA rejoining on the line; he apparently thought he was climbing when, in fact, he was gradually descending into the trees.

ACT - not supposed to do it in weather/clouds but may enter unforecast weather or sun. In Puerto Rico, over water, winds are usually light/variable, 10 kts from east; do not disrupt sea. Over a smooth sea, it's impossible to gauge your height.

Intense maneuver - 4-6 G's: big player - tough to get back on gauges. Aerial refueling - bad.

Key: be aware - always be aware of attitude, airspeed, and what's going on around me. What I do if I lose these aspects of situational awareness is say, okay - knock it off. Trouble with young guy is competitiveness: pulls that extra G, trips over his fangs, hangs in there too long, and gets into situations he can't resolve.

- Fatigue - big contributor in SDO
- Hangovers - 12 hrs bottle to throttle is insufficient; I think that 24 hours is required for all residuals of alcohol to be eliminated from the body's system.
- Diet - Wendy's, MacDonald's - fast food - bad.
- Physical Exercise (PE) - now being recognized as more important.
- A-7 - not that much different from the F-16.

F-16 SPATIAL DISORIENTATION

Major Arthur F. Fowler
56th Tactical Training Wing
MacDill AFB, Florida

BIOGRAPHY

Flying Experience:

Trainer	-223
F-4	-2,000
F-16	-800
Combat (F-4)	-385

Awards:

DFC (3), Air Medal (14), Meritorious Service Medal, Commendation Medal (2), Outstanding Unit (2), National Defence, Armed Forces Expenditionary, Vietnam Service, Longevity, Small Arms, REP of Vietnam Gallantry Cross, Rep of Vietnam Campaign.

Education/PME:

Master of Business Administration (MBA), University of Western Florida, 1980
B.S., Mechanical Engineering, University of Utah, 1969
Air War College (Seminar) 1985
Command and Staff (Seminar) 1981
SOS (Residence) 1975

Assignment History:

UPT, Laredo, 1969
Seymour Johnson AFB NC, F-4 1970-1972 (TDY Ubon RTAFB 1972)
Rivet Haste, Nellis AFB/Udorn RTAFB, F-4, 1972-76
414 FWS Nellis AFB (FWIC student instructor), F-4, 1973-76
ASTRA Norton AFB, CA 1976-77
56 Comp Wg, Osan Korea, F-4, 1977-78
4485 Test Sq, Eglin AFB, FL, F-4/F-16, 1978-80
4484 FWS (WSEP), Eglin AFB, FL, F-16, 1980-81
388 TFW, Hill AFB, NV, F-16, 1981-84
56 TTW, MacDill AFB, FL, F-16, 1984-Present

We're standard people - we have fears - I've flown over 2000 hours in the F-4, including combat and night; no spatial disorientation (SDO). F-16 - SDO is a fact of life - occurs everytime I fly at night/weather. I don't want to fly the F-16 at night and don't know any F-16 pilots that do.

We had a recent scramble to get the aircraft away from a hurricane - Friday PM party at Squadron Commander's; told we might have to fly emergency deployment the next AM - arrived home - phone's ringing - we deploy to Homestead at 3 AM. No one wants to fly at night or in the weather - raining so hard you couldn't see. If we had to eject, know we wouldn't survive. F-16 was not designed for the night/weather role.

<u>Bubble Canopy</u>: Sit up high:

- Laminations - 2-3 images - aerial refueling light, landing light, VASI's.
- No canopy bow - don't want it back.
- Glare and reflections - impede outside viewing; if turn lights down to see out, can't see any instruments.
- Formation lights - from tail on, there's just one white light only - almost impossible to see; exterior lighting not designed for night or weather either.
- Wing tip lights - blocked by missiles.
- One big light on tail but only one in front - not like F-4.
- You can't fly weather-formation in F-16 - put wingie 5 miles on your trail - it's getting to be a standard in the community. If I know I'm going into the weather, I get wingie in 5 mile trail. I do not take him in on my wing.
- Instruments way low out of view - unless things are changed in the F-16A/B, we'll have to live with it.
- I'd like to have an ADI about 6" big, in front, at eye level, so no matter where I turn my head, it's right in perfect view.

Where the ADI sits right now, you have to transition from outside to inside totally; you cannot use both of them (stay out/in) at the same time; in other words, with the present display situation, you cannot quickly come from outside, or from the HUD, to check attitude, and get back outside onto the HUD immediately.

The HUD lighting is such that if you turn it bright enough to read what's in the HUD, you can't see through it very well. So as a general rule, we'll turn the HUD down to where we can just barely see it so we can see out front. That is not only doubled, it is tripled at night.

When I go in for an air-to-ground pass, I can't turn the HUD down far enough, even with all the filters on, so I can see the ground and the target real well. I have to turn it all the way down and then I just have to guess because the CCIP and the other instrumentation out there is just too doggone bright. We talk about HUD symbology, FPM, the pitch ladders; most of the guys just turn 'em off because they clutter so much that you can't see out. We teach guys to turn 'em on enough so we can review your film later on but it's very difficult to use 'em because of cluttering and brightness.

Interior lighting - terrible. Canopy lighting must be turned up to read any instrument - worst is the DME on the HSI. Can't even see that unless you turn all instrument lights real bright. And there are no individual rheostats. I would've thought that when we went to individual rheos on the F-4, we'd have learned something. All the lights - there are two sets: I can turn up the ADI and ALT and turn everything else that's not being used, down.

The radar - in the F-4 at least we had a radar filter. Not so in the F-16, so if you turn the REO on, first it blinds you, and you can see two or three radars off the canopy, and then if you put a piece of red cellophane on it like I did, you can't see it very well. Or if you turn the REO down to get rid of most of the glare (and I'll guarantee you can't get rid of all of it), you lose some of the targets on your scope. So the aircraft, as I've pointed out, was not designed to be flown at night.

Flight characteristics: It's the neatest aircraft to fly and it's easy to fly because we put limiters on it.

There's no feel to the stick. You can't tell airspeed changes or how much you're pulling.

It's very quiet and provides no noise cues. When the F-15 hit 600 kts, you could tell--not so in the F-16. It's very quiet.

What would I like to see done to the F-16? Don't think night aircraft role should be single seat - think they should use B models and put all the equipment and navigation stuff in the rear cockpit. Don't think LANTIRN should be single-seat.

Ground Warning Systems - We've talked about 'em for aircraft like the F-16 for years. And we still don't have one - but they could have put a simple one tied in like our Bingo fuel which just flashes if the altimeter hits the preset altitude which I've dialed in; it just gives me a tone. They could have done that years ago but they're waiting for an RA and other fancy things and we still don't have it. I think that could have saved several lives in the F-16. So we need some sort of a warning tone, a simple one; don't get so doggone cosmic. Get it to us and get it to us tomorrow because this is when we need it. By the time we get it, I won't be flying, and I want it now so I can continue to live.

- We need a big ADI
- We need rheostats
- We need REO night filters

o We need the instrument group moved up to where we can see 'em, so you can transition from outside to inside easily.

And one thing I'd like to stress because I've heard a lot about it here (I hope that's wrong); that's improving the HUD, improving the HUD, improving the HUD. Well, the HUD was designed for one thing - that's a weapon systems platform. We ought to quit talking about flying instruments on the HUD. The HUD should not be an instrument to fly instruments with. It ought to be used for what it was designed - that's to drop bombs and kill MIGs. When it comes time to fly instruments, use the primary ones. Don't use that one that is so spatially disorienting. And if we can do that, I think we're a long way away from the accidents that are caused by SDO.

Don't teach guys to use the HUD. Teach 'em to, if they want, to turn the doggone thing off when they're flying instruments 'cause it's not needed. Go back to primaries. That's my little pitch about the F-16. I'm open for questions.

Editor's note: Unfortunately, Major Fowler's Question and Answer session was not recorded; the following are excerpts from notes taken at the time.)

Maj. Harold Gonzales, Hill AFB: HUD is useful for wind-direction data.

Mr. Joe Bill Dryden, GD, Ft. Worth: Many of us use the HUD, the difference is probably in experience, background and especially training. Training use of the HUD is crucial, and when one is properly trained, he can fly good instruments safely by the HUD.

Another Pilot: Looking at the world through the HUD under certain conditions can cause confusion and spatial disorientation.

Mr. Robert DeGiorgio, Lear Siegler Astronics, Santa Monica: I use all my instruments flying the A-7, including the HUD. Being emotionally aroused contributes to SDO, buy my training has helped. Maybe we're not giving sufficient instrument training, especially at RTU, before sending new-to-the-Air Force F-16 pilots to foul-weather bases like Hahn or Kunsan.

Dr. Richard Malcolm: There are two aspects to the orientation decision - the macro or big picture and the micro picture. The HUD provides only the micropicture - a vernier scale that calibrates the outside world, like looking through a 16o porthole. It does not provide the immediate Big Picture as does an Attitude Indicator. Whereas oldsters use all the old tricks, newbies may not have as strong an idea of the macropicture: you first must make the macro decision - am I upright or inverted? Then, am I climbing or diving? And if so, about how much? An analogy is in reaching for or grabbing an object. The brain's initial orders are ballistic - then fine tune. The HUD only enables fine tuning - which is only the latter half of that orientation decision.

Another Pilot: The HUD is primarily a weapons system - to simply calibrate that porthole on the world. Even if everything were up there, would still want head down instruments.

Another F-16 Pilot: I'm not sure we can attribute fatal class A's to the HUD. Many of these mishaps involved experienced fighter pilots. Maybe we need to fix the cockpit, canopy, feedback, etc.

Col. David Milan (Fromerly F-16 Joint Test Force Test Pilot): Several of you have expressed rather extreme opinions regarding the HUD, not necessarily regarding mainstream. Others use it primarily.

B/G Pruden: My experience corresponds to Maj. Fowler. In weather, I tend to go head-down. The real issue is not HUD vs. ADI - we need to maximize the technology to create something that's better than HUD or ADI - maximize the information cross-tell from all these instruments and sensors.

Mr. Bill Wilson: ENASI, WPAFB: The Avionics guys need to know whether it's to be head-up or head-down, or both. Comment: Maybe the answer is that the pilot needs both: the HUD for the micro-picture, and a big attitude display immediately below the HUD to provide the macro-picture practically within the same field of regard.

OVERVIEW OF
HOW THE BRAIN AND PERCEPTUAL SYSTEM WORKS

Dr. Richard Malcolm
Maltech Research Corporation
Oakville, Ontario, Canada

BIOGRAPHY

Richard Malcolm was born in Ottawa, Canada, in 1941, where he received his primary and secondary education. He enrolled in the Royal Canadian Air Force in 1959. Through the ROTP, he attended the University of Ottawa, majoring in solid state physics, and earned an Honours B.Sc. His summers were spent at the RCAF School of Aeronautical Engineering, and during that time, he undertook course work in guided missile and space technology.

In 1964-65, Richard was granted leave from the Air Force and earned an M.Sc. in Nuclear Physics from the University of Ottawa. Principal areas of study were on the scattering and detection of high energy neutrons. Upon return to the RCAF in 1966, he was posted to the RCAF Institute of Aviation Medicine in Toronto, Where he was responsible for designing a nuclear scanner for use on the human centrifuge. Richard's inventiveness resulted in a product which was ten times more efficient at detecting radioactive Xenon than the best commercial devices of the time. He also was the co-inventor of an automatic blood pressure measuring system. Machines based on this principle are now standard in intensive care units throughout the world.

From 1967-70, Richard was posted to the Aviation Medical Research Unit of McGill University, Montreal. While there, he studied the perception of motion, and how the nervous system adapts to motion. At the same time, he held teaching appointments in neurophysiology, neuroanatomy and biophysics. During this time at McGill, he earned a Ph.D. degree in neurophysiology.

In 1970, Richard was posted to the Defence and Civil Institute of Environmental Medicine (DCIEM), in Toronto, Canada. He published numerous papers in scholarly journals on the workings of the organs of balance, and while at DCIEM, was a member of a joint Canadian/United States team doing research on the NASA Space Shuttle. He was one of the two Canadians designated to fly as a mission specialist on the Space Shuttle.

During this time, Richard patented a number of inventions, including a completely new concept of avionics for use by pilots flying on instruments. This system has been tested by military and civilian agencies in both the U.S. and Canada with favourable results, and the "Malcolm Horizon" is now expected to become a standard flight instrument over the next decade. This invention is now being manufactured by Garrett Manufacturing Ltd.

Roughly half of Richard's time since 1970 has been spent in the study of nutrition. The majority of information published on this subject is inaccurate or misleading, and Richard undertook to trace a large body of nutritional writing back to its original sources. The results of this exercise is a body of knowledge which is scientifically accurate. Richard has frequently lectured to groups of professional health care disciplines on nutritional subjects, and is often consulted by medical practicioners regarding their patients.

In 1979 he retired from the Armed Forces with the rank of Major and founded Maltech Research Corporation. Maltech is in the business of developing new products for industry. It assesses the technology, arranges the financing and puts together a team to develop each new product. It then manages the project to the point where it is licensed to a manufacturer. The company has handled projects in such diverse areas as: blood sampling equipment, an all-terrain vehicle, an inflatable sleeping bag, robotics, microwave telecommunications systems, nuclear magnetic resonance detectors, time-of-use metering of electric power and data interface terminals.

In 1983, some of Richard's pioneering work in neurophysiology was recognized when he was asked to give the Howard G. Baker Lecture to the plenary meeting of the American Laryngological Association and the American Neurological Association in New Orleans. He was also accorded the honour of presenting the 18th Harry G. Armstrong Lecture to the Aerospace Medical Association, in Houston, Texas in "recognition of his outstanding contribution to the field of Aerospace Medicine".

What I'm going to try to do is to present to you an overview of how the perceptual equipment in our bodies works. And Grant has given me one hour to do this, which is a life study in its own right. I'm going to take the added task of doing it in non-technical language because I think that if we can understand it in the English we use every day, then we'll be a long way farther ahead than worrying about whether we really know what these terms mean. Now there is a lot of technical information that I am going to be presenting to you in this mode and I don't want to so much focus on that, as I would like you to just sort of get a feeling for the subject. And the feeling I want to use the information on the slides to convey to you, the feeling that I want you to take away with you, is the richness associated with our everyday sensory experince. It's no good to talk about a visual experience, it's no good to talk about, say, a hearing experience; all our waking experiences are enormously rich. They include the room around us, the feeling of our clothes, how we happen to feel internally at the time, as well as, our emotional state associated with the situation at hand. When we form a perception, and then ultimately, a memory of that event, that memory or perception contains all that information tagged on to it. And if ever we want to refer back to it, we get the whole thing back. If ever we want to make a decision, the experiences we've had that have similar tags on it also come into play when we make this decision. So the act of perceiving, the act of cognition, where we do thinking about things, where we manipulate those perceptions in our minds, those acts always involve the full panoply of perception, the full sensory experience. So what I am going to do now is show you a whole series of slides which is designed to give you an awareness of the machinery of perception and just how diverse that machinery is. I'm going to start off showing you the very basis for perception.

The very basis for all perception is, of course, the nerve cells, (Figure 1, a typical neuron) and I want to give you just a little tiny run down on how the nerve cell actually works, what electrical events take place when we fire a nerve. A nerve is made up of a cell body in which there is a nucleus. The nucleus is the factory that makes all the food that goes into feeding this equipment and allows it to grow. An electrical event takes place in there which causes an electrical discharge, a voltage to go hopping along this pipe and to different places, and it is always one direction. In other words, it will go along this wire, called an axon, to another place. Or it might branch out here and show up at these terminals. (Terminal boutons or synaptic knobs.) So that's the way information gets from one place to another, electrically.

Now nature had a problem to solve, though, in getting all these electrical connections encased in this tiny head box. You need to understand that in terms of connections, the actual physical connections between nerve cells, there are more of those connections in our head than there are stars in the entire universe, that we know of. Now if you did this electrically, the interference problems would be awesome. So what nature has chosen to do is a different thing. Those little connections that we saw out here on the side actually form not an electrical bridge but a chemical bridge (Figure 2, electron micrograph of three synaptic knobs lying against the membrane of a dendrite), and so those little buttons line up on the surface of that big blobby cell to which it wants to transfer information, and there are these things called synapses which are little tiny spaces between the two electrically excitable tissues, and you can see that they measure about one micron of gap-width. So you are looking at something which is starting to approximate a number of molecular diameters and that's all. And when that electrical field comes down to the end of that button it causes some chemicals, which are stored up here, to be released and to migrate just through diffusion down onto the tissue beneath them. When it gets here, to the tissue below, it causes that cell here, to reinstitute that electrical event. That discharge, that electrical spike, is then propagated onto the next one. And so there are two things that I want you to take away from here. First of all, that perception is an electrical event. All thinking, all feeling, all events of which we are aware that go on in our body are simply

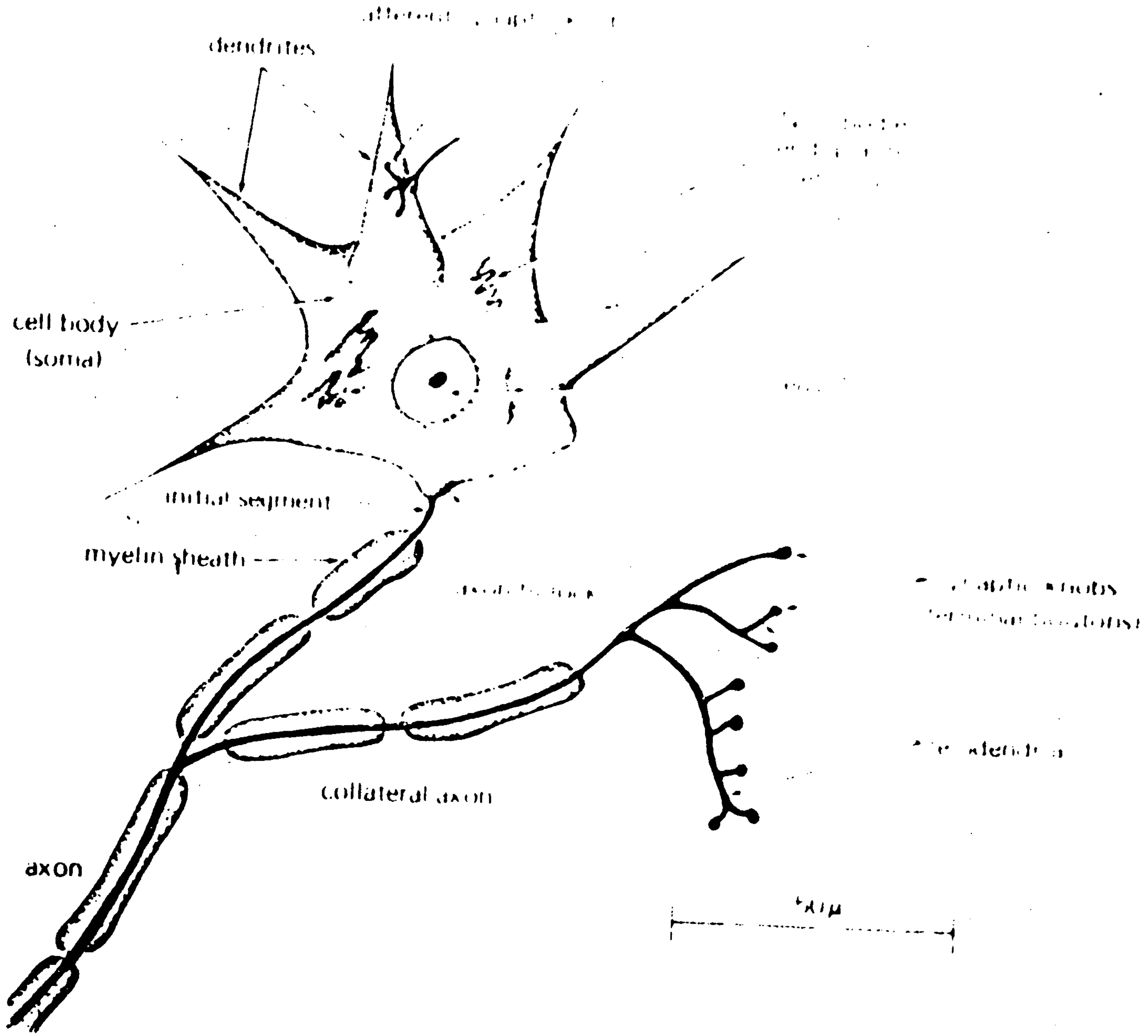


Figure 1: A typical neuron.

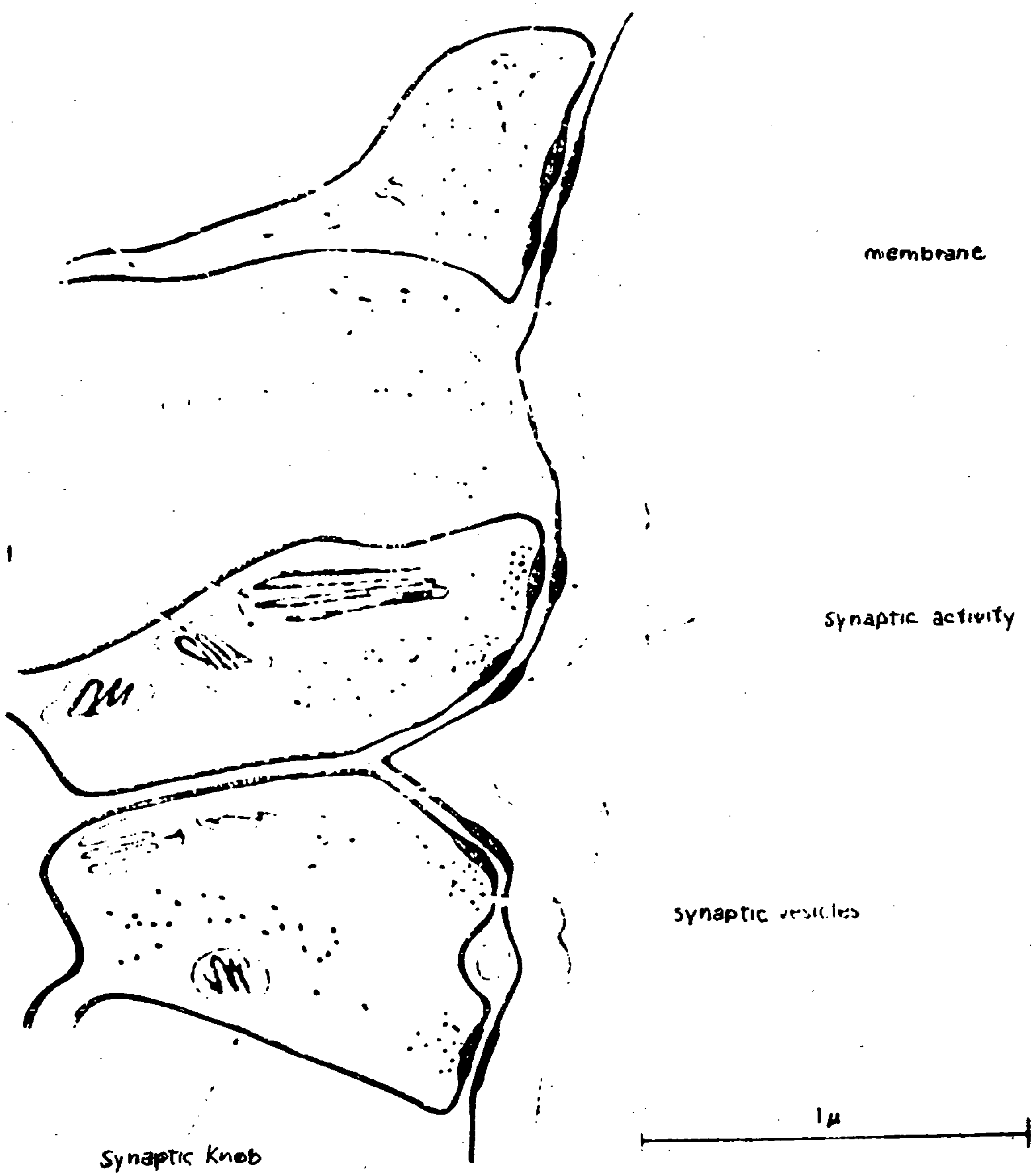


Figure 2 Electron micrograph of three synaptic knobs lying against the membrane of a dendrite (After Palay 1958)

electrical events; and second, the transmission from one place to another always occurs over these junctions which are chemical. And that means that, say there was an electrical interference in this area, I can't have that interference turn that particular cell on; it has to actually influence the chemistry before I can propagate on to the next layer of central processing. So it's a very crafty way that nature has got around the business of compacting electrical equipment into the small case and not having a lot of cross-talk.

Now, it has been worked out to a reasonable degree how that molecular chemistry works, (Figure 3, a model of synaptic transmission). It seems that when the electrical spike or depolarization arrives here at the membrane, (and this is the gap that was called a synapse), it releases that neurochemical, and these little chemical molecules come along here, (and normally the channels, these channels through which ions can flow, are blocked by molecules which occupy these sites) and it is thought that the chemical that is released up here at the orignating axon crosses this synapse, and when it gets down into this area on the receiving nerve, it opens the channel, so to speak. It just causes the blocking molecule to move out of the way, and allows a flow of sodium in. Actually, that's why our bodies contain so much sodium. It's a very important chemical to us. The neuro-chemical moves the blocking molecule (like opening a door), and allows sodium to go rushing into this interior part of the receiving cell down here. That transmission of the current like that causes the membrane of the cell to propagate that electrical pulse all the way down to the end of that cell and on down to the next one of these sending units, or synapses.

So that's how perception takes place. When I bump my toe, I cause that electrical event to come along the nerves and waystations all along here and go through a whole series of these things, where it is electrical, chemical, electrical, chemical, all the way up into the brain. And that's why it takes time. It's not an instantaneous reaction; it doesn't travel at the speed of light, in fact, pain fibers are very slow. They might only travel a meter per second or so. You can appreciate that if you do bump your toe; your first reaction is to pull your toe away because the touch and pressure fibers are very fast. They might take 200 milliseconds to get to the brain, yet the sensation of pain grows over a period of 1 or 2 seconds because it takes that long for that pain message on the slower fibers to get up to the brain. That's one of the things you need to bear in mind, that the information takes time to get from one place to another. And that has proven very useful for physiologists in mapping out how the brain is actually organized because you can measure the time it takes to get to different places.

Now, how does bumping my toe or touching something or smelling or seeing something actually take place? How do I convert a mechanical or chemical event, or a taste, or light event in the retina of my eye; how do I convert that into the electricity in the first place, into the signal which is then carried on to the brain? Well, a very generalized model is as follows,

Figure 3: A model of synaptic transmission (a) Release of transmitter substance from a synaptic vesicle through the presynaptic membrane. Molecules of transmitter substance open pores in the postsynaptic membrane when they impinge upon it. (b) The postsynaptic membrane enlarged. Molecules of transmitter substance occupy receptor sites on the membrane and move the adjacent barriers at the openings of pores through the membrane (After Eccles, 1964.)

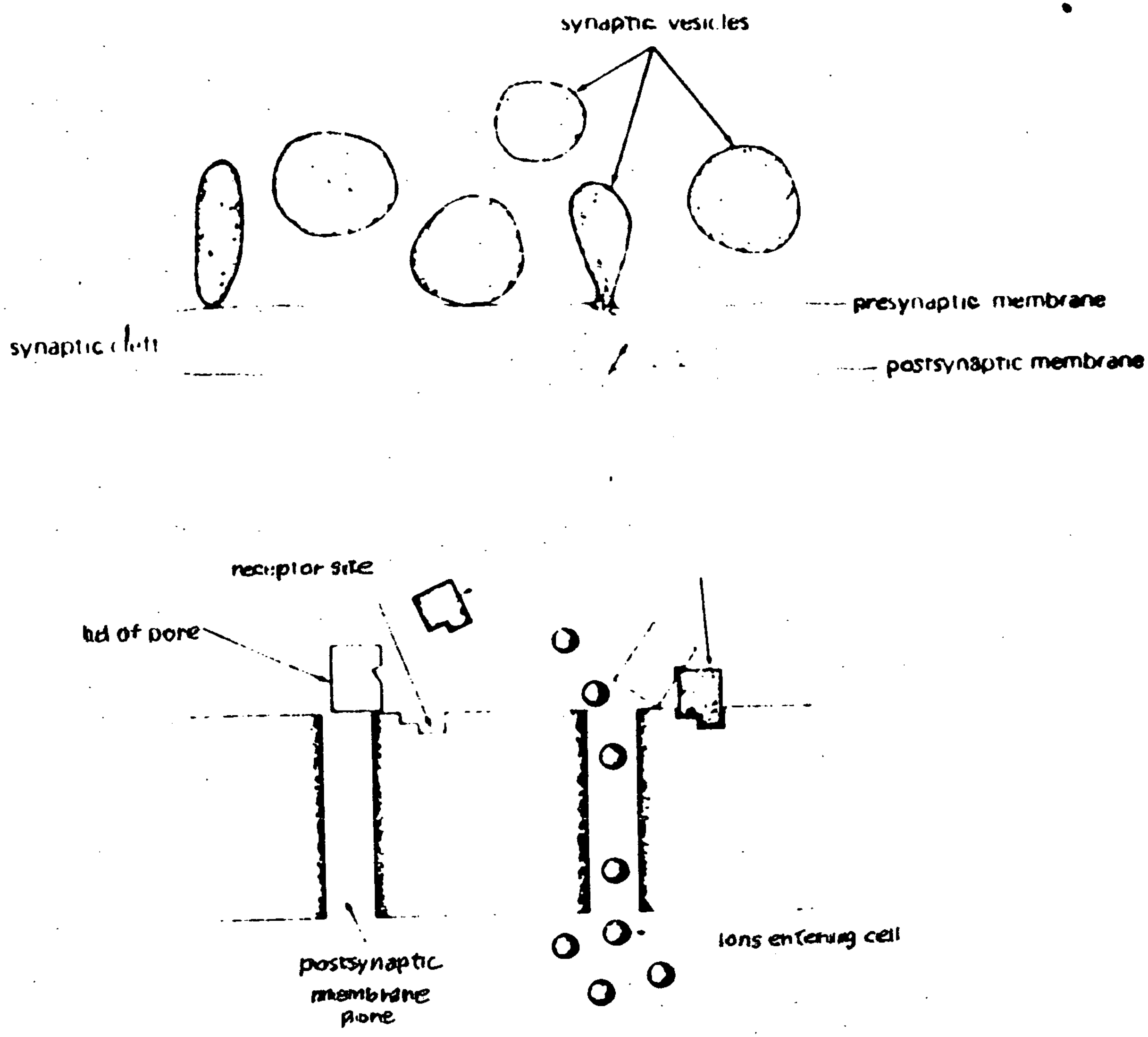
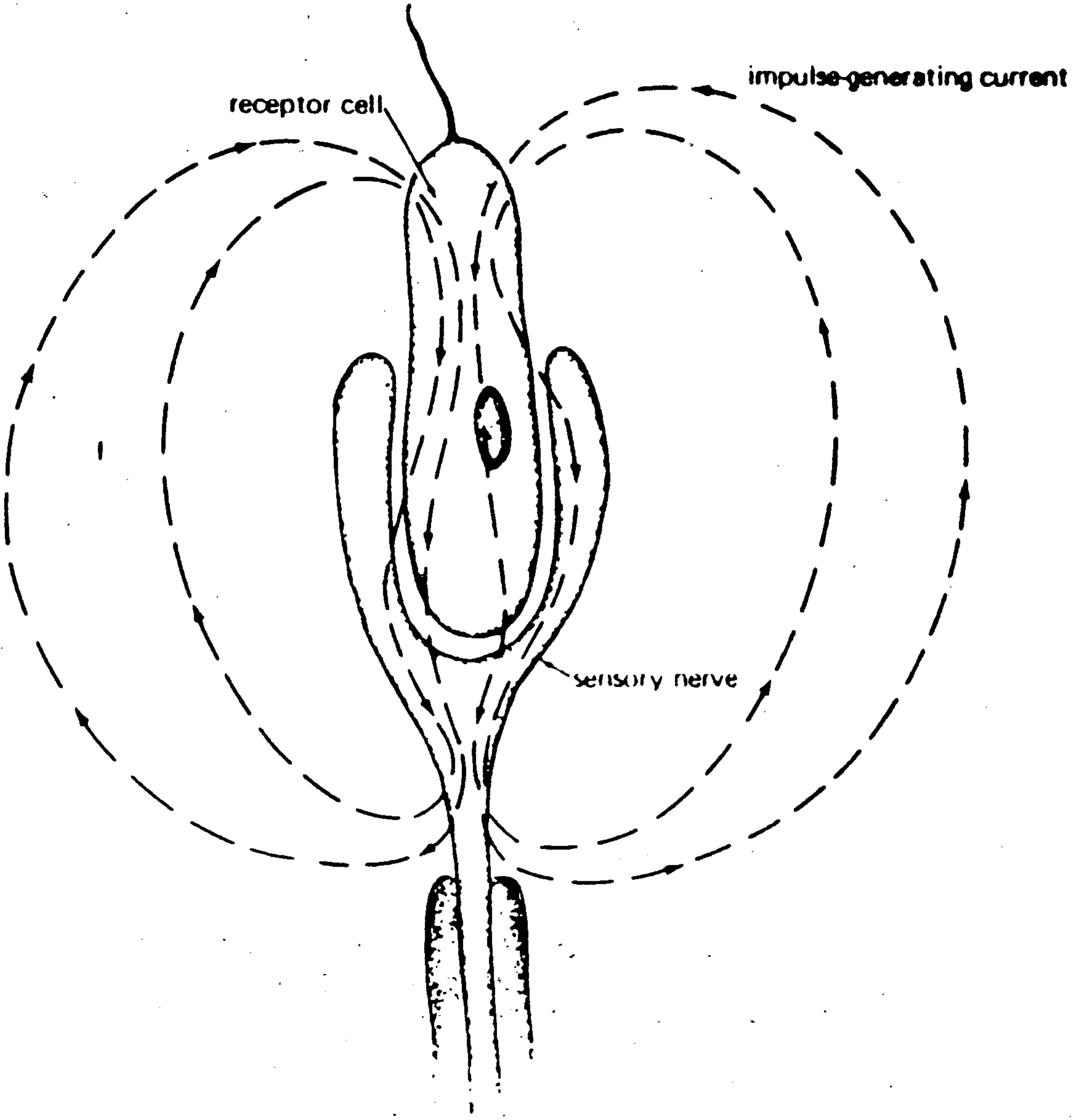


Figure 4: The receptor cell does not itself generate an impulse, but the depolarizing current that flows into it when it is stimulated also flows through a closely apposed sensory-nerve terminal and depolarizes it sufficiently to generate impulses there.



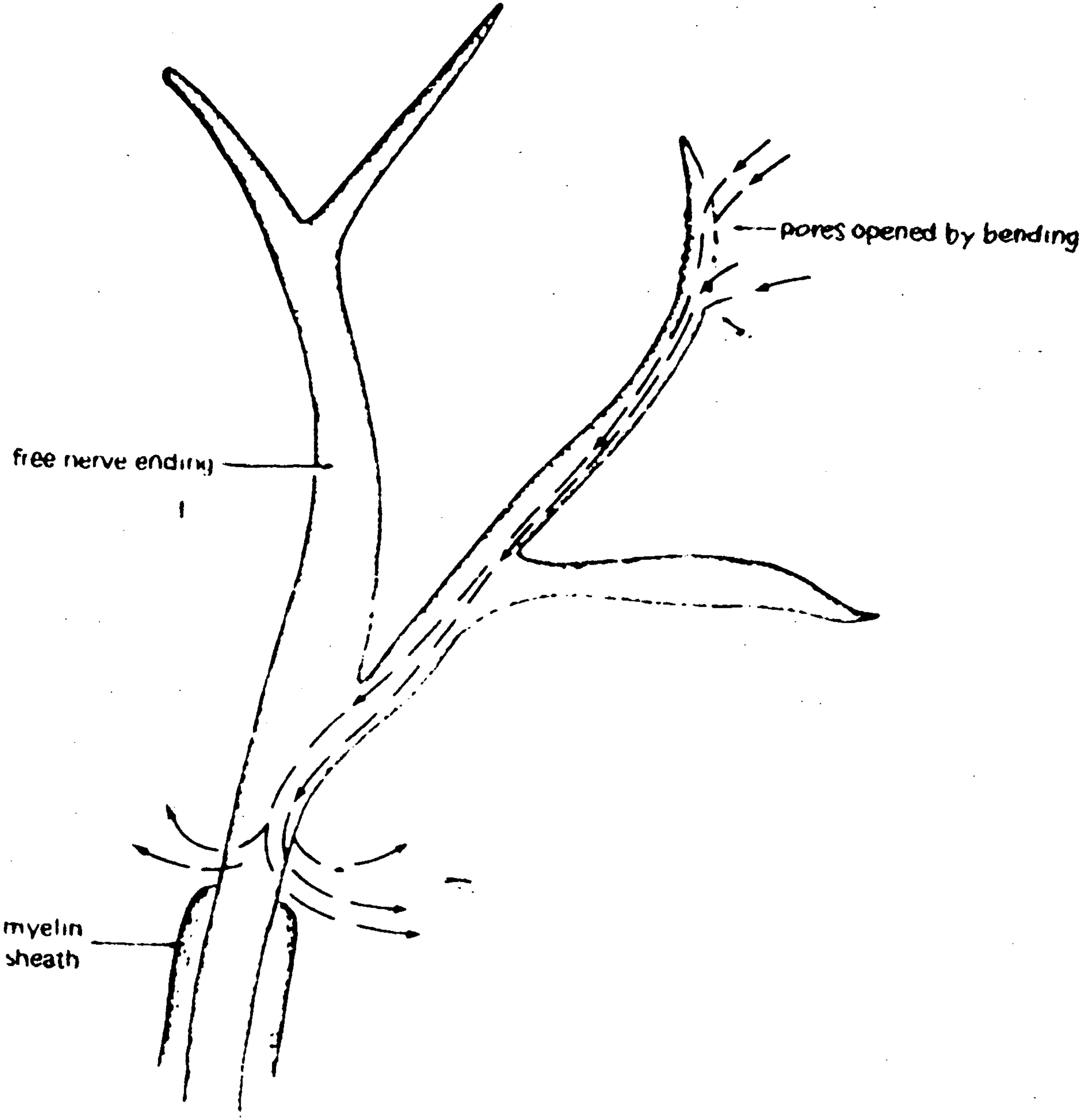
(Figure 4, receptor cell model). The thing you need to remember is that this is not even typical, it just explains the process. In fact there are at least 20 different types of receptors spread throughout the body; we will talk about what some of them do in a moment, but first you have to understand how they work. You can see that there is a specialized cell. Why specialized? Well, very early primitive animal, (and by primitive animal I don't mean someone who doesn't fly,) what I mean is a very simple organism, very low on the phylogenetic scale. They used to have maybe only one or two different kinds of cells. And cells which, say, we would call muscle cells since it causes things to move, might also be a receptor, so that the particular animal might be caused to move as a result of the chemical stimulant. An example would be a simple organism in water: when chemicals are present they swim faster to get out of the way. Temperature would also affect them. They would swim faster in that particular environment and they couldn't distinguish between the two. Something made it go faster. There could be maybe five different things that could make it go faster. Well, when you have that kind of sensory apparatus, what happens is that you can't distinguish between different events. They all feel or are perceived the same by simple organisms.

Well what we who are higher up on the phylogenetic scale have done as a strategy is we are going to specialize. Specialty means that we have to have diversity. That means that you have to have lots of different things capable of distinguishing between temperature and light and different chemicals in the environment, and pressure and touch and vibration and sound and so forth; but when you have that diversity, it also means that you have to have a lot of equipment which is going to use that information. And that's why we have a big brain. It's because all that richness of experience is now offered to us. We now have to be able to distinguish the significance of events which are different in terms of their quality. The mechanism for doing that is a sensory nerve cell.

Here is the nerve, itself, which is going to carry the information on towards the central nervous system. And what seems to happen is that there is a special receptor cell in most cases, and it could be stimulated. It could be light that is stimulating it, it could be touch, it could be whatever turns this on, what literally causes that chemical reaction in which sodium, again, flows into it; and the little pump inside pumps the sodium back out, maintaining high potassium on the inside. This is simple chemistry. That action of the sodium flowing in and being pumped out again sets up an electrical field, and that electrical field is now felt by the sensory nerve ending here which turns on that nerve fiber and sends electrical impulses down along the path that it's intended to go. That's the basis for all sensation. It's the conversion of the event to be sensed into an electrical pulse.

There are other ways of doing it which are a little less sophisticated, and in this particular case (Figure 5, a free nerve ending) it is thought that in these three nerve endings, just the act of bending it stretches open these little pores along here which allows the sodium to flow in, and that sets up a

Figure 5: Ion flow through pores opened in the membrane by mechanical distortion of a free nerve ending



current like that and the pump is out here pumping it back out and all that is enough to depolarize that membrane and cause the information to start on its path towards the brain. So that's the basis of sensation. It starts at that point. Interesting things.

Let's go a little bit farther into detail to show some of the finesses that nature has played. This particular sensor (Figure 6, called a Pacinian corpuscle), is thought to be mostly a vibration sensor, because it adapts very quickly. What happens is that it is a mechanical thing (they're embedded in the skin); if you compress it, for instance, and if you squish the top, these layers, which are like the layers of an onion, distribute the force mechanically over the whole length of the receptor part. And again, because it is a mechanical thing, the distortion causes a current and then a spike of electrical activity to be propagated. Two points: these onion skin arrangements are a way of damping the reaction; it allows the reaction to not take place so instantaneously; it provides a sort of response time constant which you will see here (Figure 7, generator potentials from a Pacinian corpuscle during application of an electrically controlled tactile stimulus). You'll notice that if you are given an instantaneous spike, (which is the top line on the upper left diagram), if you push this thing very rapidly, then the electrical activity rises very rapidly and very rapidly decays again. But, conversely, if I push a little slower (as at the upper right), the electrical activity rises slower and decays at the same rate. And if I push really, really slowly (as at the bottom diagram), at the same amplitude, but I just take a long time to do it, you'll notice that the electrical activity doesn't get very high. That's part of the richness. The response that we have is not all-or-nothing; even though the electrical event is all-or-nothing (the nerve cell either fires or it doesn't fire), but it's pulse-coded frequency modulation. And that means that I have an analog signal in a digital form.

Now I have instantly converted this analog thing here into a train of action potentials, a whole series of little electrical spikes that are fired in time and the rapidity of the firing is the thing that I am measuring. What I want you to notice is that I now have analog information. The firing of these cells would tell me how fast that particular corpuscle got pushed. All right, 'that's part of the richness that I am talking about. We can not only discriminate that a push took place on that particular part of my fingerprint but it can also tell you how fast it is. And that is one of the ways that we are able to perceive texture because when I rub my fingers over, say a cloth, depending upon whether the cloth fibers are fine or big will depend upon how fast they indent the surface of my skin. And so the richness of my environment includes the ability to detect texture. That's how it happens.

We have all these fibers that rise up down here in the peripheral part of our body (Figure 8, extra-lemniscal somatosensory pathway), and you'll notice that this is just intended to be a section of my spinal column. You see these fibers all enter and there are these chemical junctions, and some of these fibers come up one side of the spinal column, other fibers come up the other

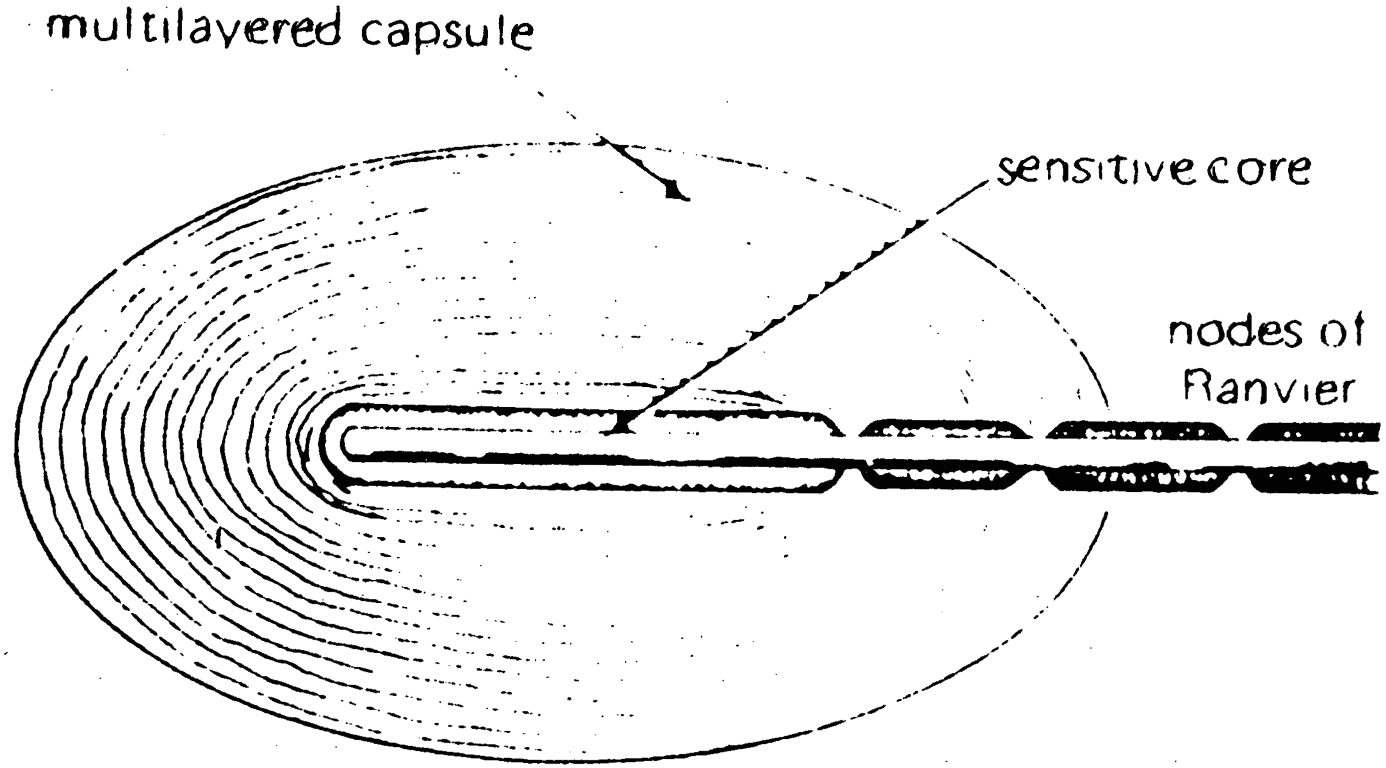
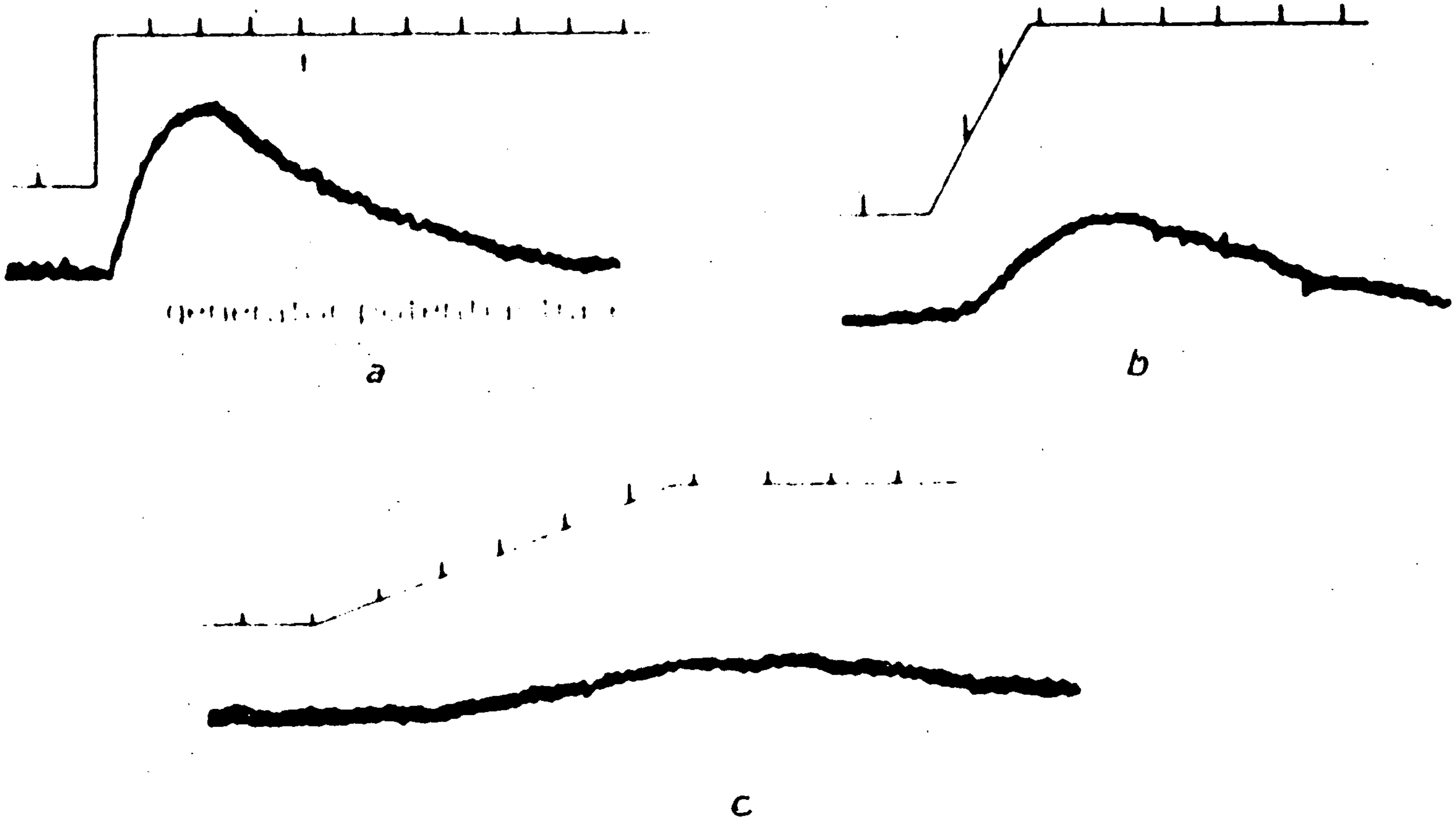


Figure 6: Cross section of a Pacinian corpuscle showing the core consisting of a sensory nerve-ending.

Figure 7: Generator potentials from a Pacinian corpuscle during application of an electrically controlled tactile stimulus (a) The stimulus onset as brief as possible. The stimulus stays on after application. (b) The stimulus onset occupying about 2.5 msec. (c) The stimulus onset occupying about 5.5 msec. (After J. A. B. Gray & Sato, 1953)



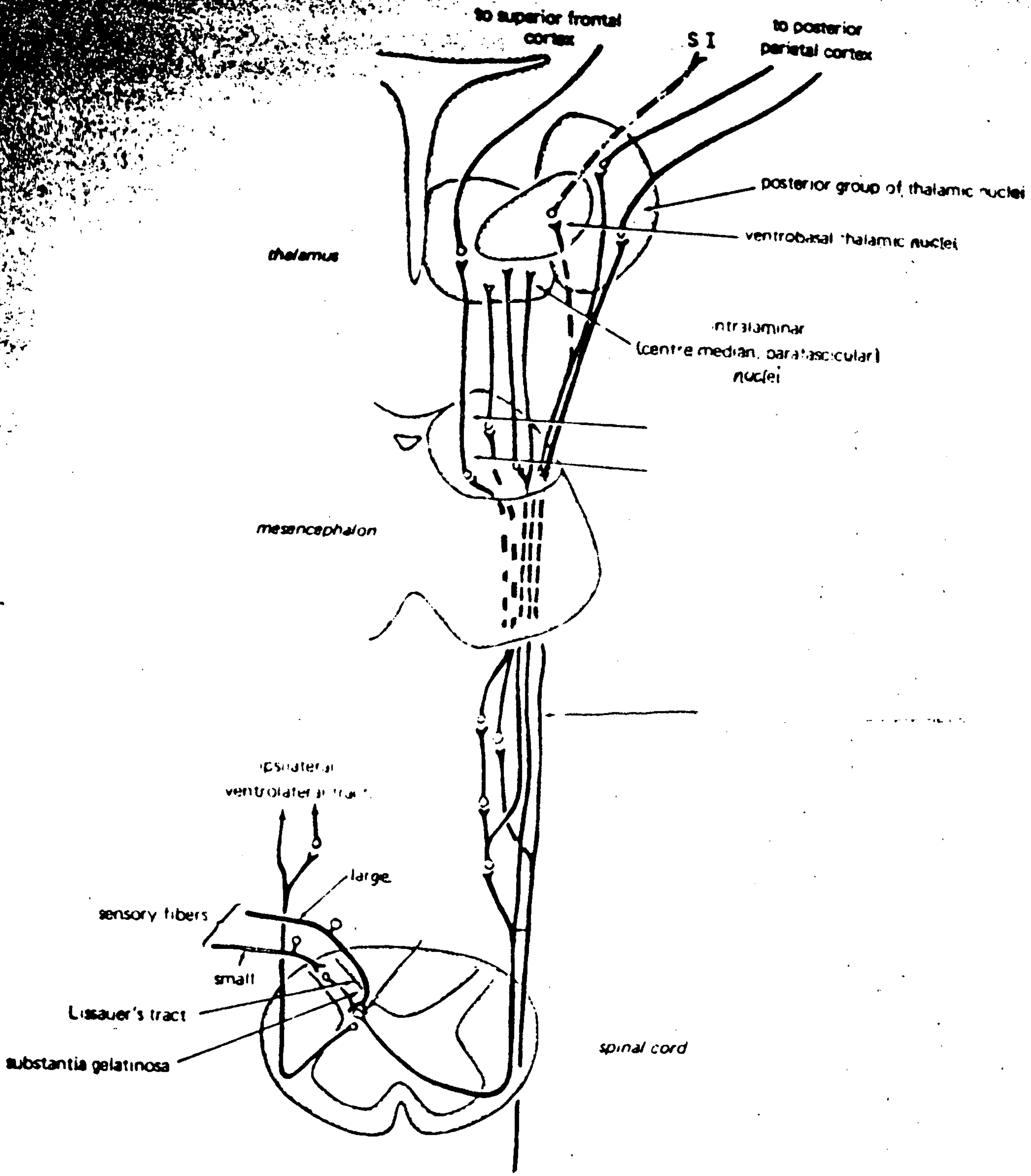


Figure 8: Extralemniscal somatosensory pathways

side of the spinal column and they form these tracks. Look at all these interconnections. There, there, there; more are higher up at the base of the brain; look what is happening: there are more of these connections and they get all the way up here in the brain where there is a section of the brain called the thalamus (the only technical word that I am going to use) and that's a switchboard. All this information comes in and the thalamus has to decide: one, whether you're interested in it and let the information go up to the part of the brain that thinks and feels; and two, it has to decide where it is going to send it because why do I need that information?

Now, what's interesting is that you can pre-load parts of the brain with programs that are going to act only if they get certain information. For example, if you're going for a swim in some murky water off the beach near your cottage and somebody says to you, "I let the weeds grow around here, don't worry about it," and if you feel something brush your leg, well that's weeds. But if somebody says to you, "Well, that water has eels in it;" you then feel the same little brush against your leg and somehow you can magically walk on water. And it doesn't take you a long time to decide whether it is grass or eels. Bam! I mean it happens that fast. What you have done is to preload the system; the information about that little bit of pressure comes ripping up here and is now organized in advance to where it is going to go, and what kind of information you are looking for, as opposed to, say, somebody singing a song to you. You are not going to listen to that song. This is important stuff, these eels. So the thalamus, the switchboard, is very active in deciding what it is that you are going to attend to and how you are going to attend to it, and where the information has to go in order to be used.

The other thing I want you to notice about this is all these interconnections. You'll see it in the next one (Figure 9, lateral view of the brain and divisions of somatosensory system), which is a different kind of a slide. It just shows more of these tracks winding up in different parts of the brain. What I want you to get from this is that every time there is one of these junctions, not only are you relaying information, but you are changing the quality of that information. Those junctions, in fact, act like a leaky integrator. They can act like a differentiator; they can sum signals, they can differentiate signals, they can inhibit, and they can enhance. There is all kinds of signal processing which is going on at every one of these junctions. You saw how many there are. That's one of the reasons why, when you finally get up into the brain, we'll see a little later, there is very little resemblance in the brain to what actually occurred outside. We have translated it into a brain-machine language which bears little resemblance to the real features that have been perceived.

But that's important, because the brain-machine language is sensitive to training. That's why training is so important. You start to interpret things in terms of what and how you have been trained to interpret them. Somebody cold in a new environment often doesn't know what to do because he doesn't know how to interpret what is coming in. First time I sat in front of a HUD

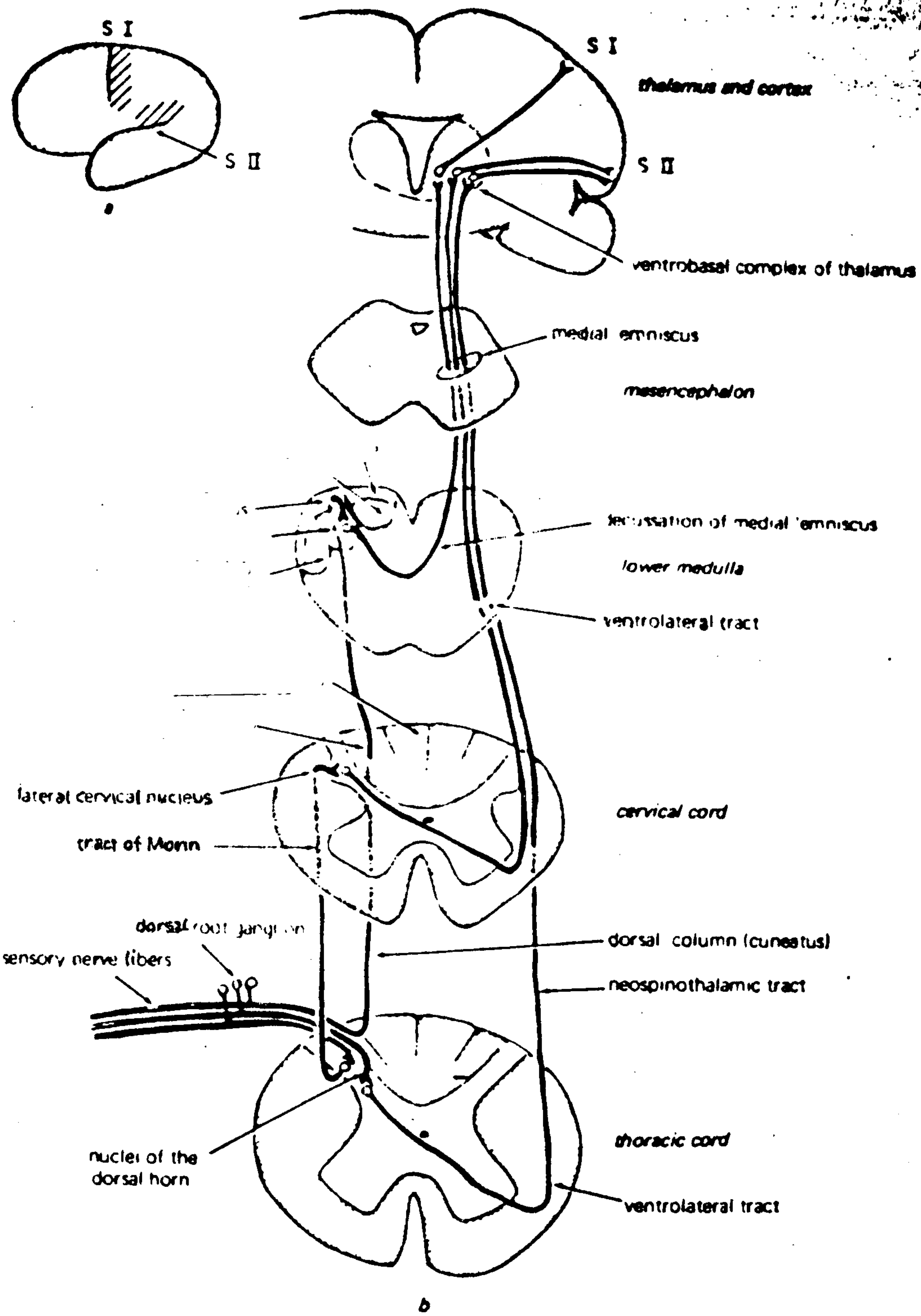


Figure 9: (a) Lateral view of the cortex showing the location of the first and second somatosensory areas (S I and S II). (b) Three main divisions of the lemniscal somatosensory system, including the dorsal columns, the tract of Morin, and the neospinothalamic tract. (The lower sections are shown on a larger scale than the upper sections.)

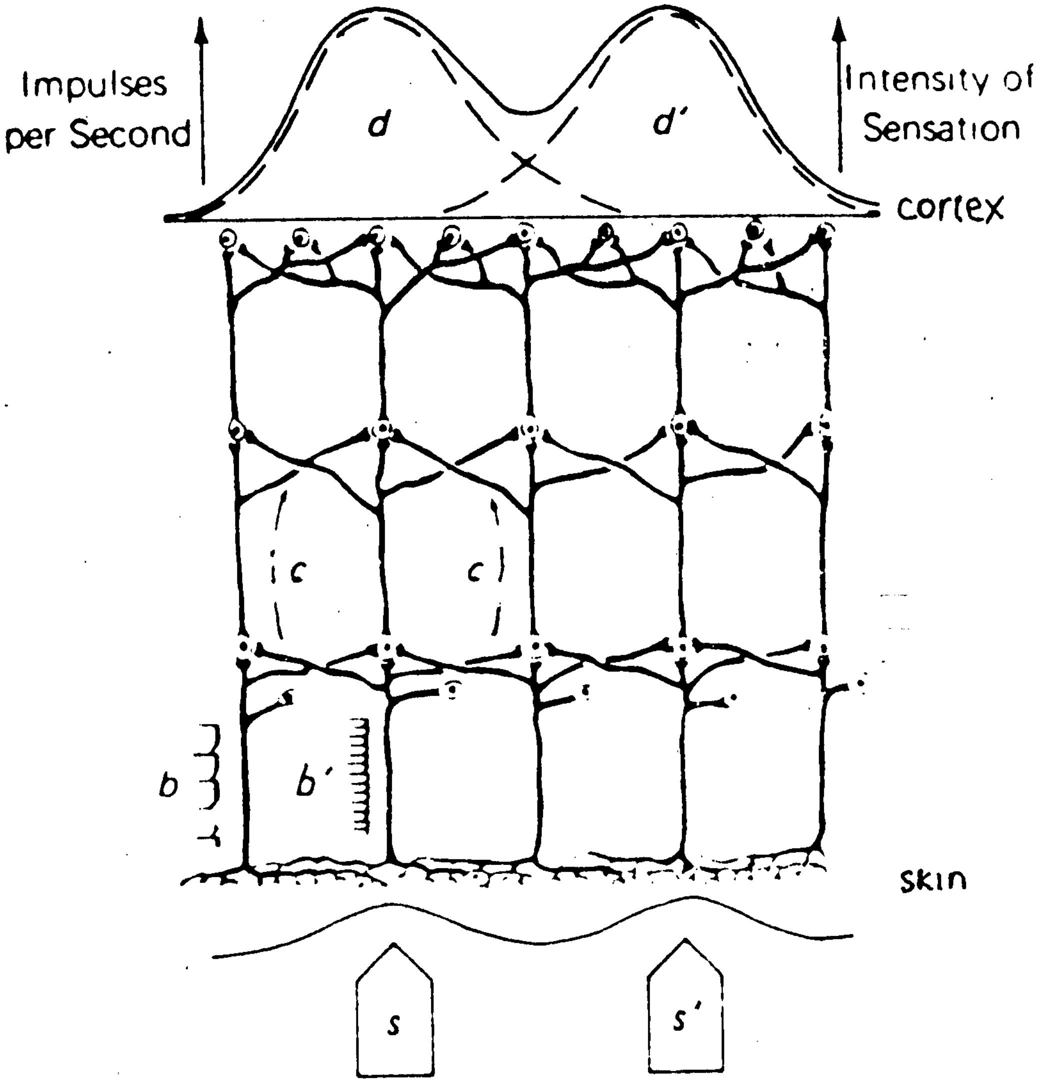
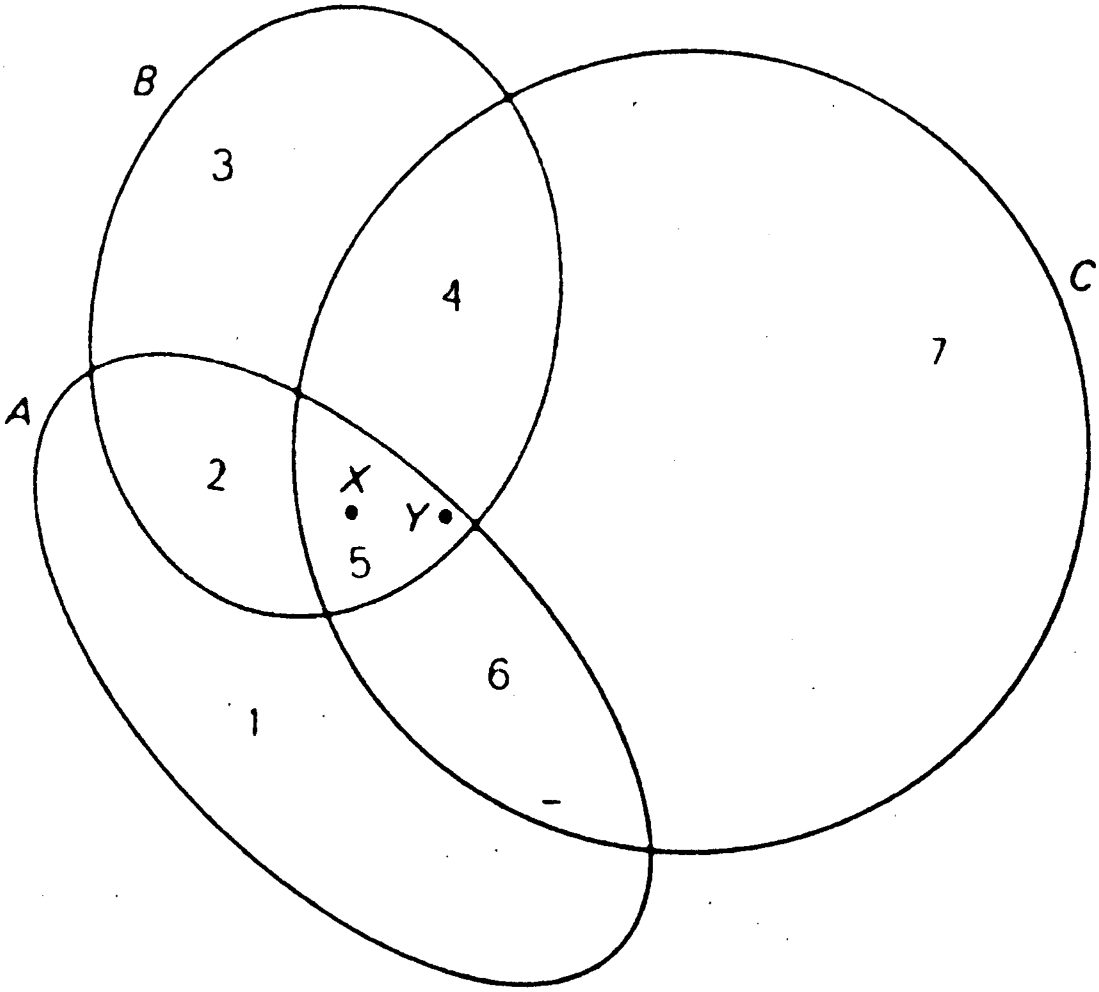


Figure 10 Ruch's illustration of the neural mechanism of two-point discrimination The two stimulating points are indicated at s and s' b is the firing rate of the receptor stimulated at the periphery of its field by s, b' the firing rate of another receptor stimulated at the center of its field. The arrows c show how the activity is concentrated on a few central neurons in the thalamus resulting in as clear a discrimination between the activities d and d' generated at the cortex as at the skin, in spite of overlapping connections along the way (From Ruch, 1960)

Figure 11: The peripheral fields of three cortical neurons, showing how the firing pattern (not taking into account gradations in firing rate) can indicate in which of seven zones a stimulus has been applied.



it was pretty. But that's it, because I didn't know what it meant. And you have to learn what all those things are. And those learning linkages that you form are part and parcel of all the signal conditioning that goes on.

Now there is another thing that I want you to be aware of in terms of the richness of the sensory system. And it is illustrated in here (Figure 10, neural mechanism of two-point discrimination). Here we have little nerve fibers that are, say, in the skin; and say that what they are sensitive to is pressure like we were looking at earlier. And this is the stength of the signal, two points on the skin; and you'll notice we are measuring the strength of the pressure and therefore the firing of these little nerve endings that are responsive to that as the height above zero of this line here at the bottom of the diagram. So there is the zero axis and you notice the amplitude on here is something like about 4 inches. Well, what happens is, because I have this network now of nerves going up to the brain, we also have another system in our sensory apparatus that sends branches off to all its neighbors. So say this fiber here has a branch going off to that neighbor, and a branch going to that neighbor. Those branches inhibit whatever is on the neighbors. They subtract from the activity that would normally be felt there. And you'll notice that at every station these branches exist. So what we have here is a firing, with lots of action potentials per second here, not so many here. By the time that gets inhibited at every waystation, and this gets inhibited at every waystation by this one, there is a big contrast improvement by the time they get up to the brain. What it means is that this guy has gotten louder compared to the two beside it, because the two beside it have been inhibited. And so the relative amplitude between the two in the brain is much larger than what it was when it started out. And what this translates into, is our ability to discriminate between two fine points. You'll notice there is a sharpening here in contrast. That's a contrast-enhancement circuit. In fact, the picture sent back from Ranger on Mars had an identical algorithm written on the PDP 8 for their pre-conditioning, before you look at them on the television, to improve the contrast of what was being viewed out there. And all our sensory apparatus contains this collateral inhibition, this ability to inhibit your neighbors so that the signal becomes sharpened and increases in gain.

Now, how does that translate into richness of experince? Well, supposing that this is the sensory field of a nerve located there (Figure 11, the peripheral fields of three cortical neurons, showing how firing pattern serves to localize a stimulus). That is, if I poke it right here, I get a bigger response and all the way out to the end. And if I poke it right here, I will get a tiny response from a nerve located there. Similarly, for this guy A and this guy B. So I have three nerves now. Now if I have a poke located at X, you'll notice what happens. The nerve located at C here feels less of a response than it would at Y. But the nerve located at say, the center of A, feels not much difference because in terms of the radius of A there is not a great deal of difference between X and Y and there is a greater difference at B. So that says to me that if I compare the outputs, using this collateral

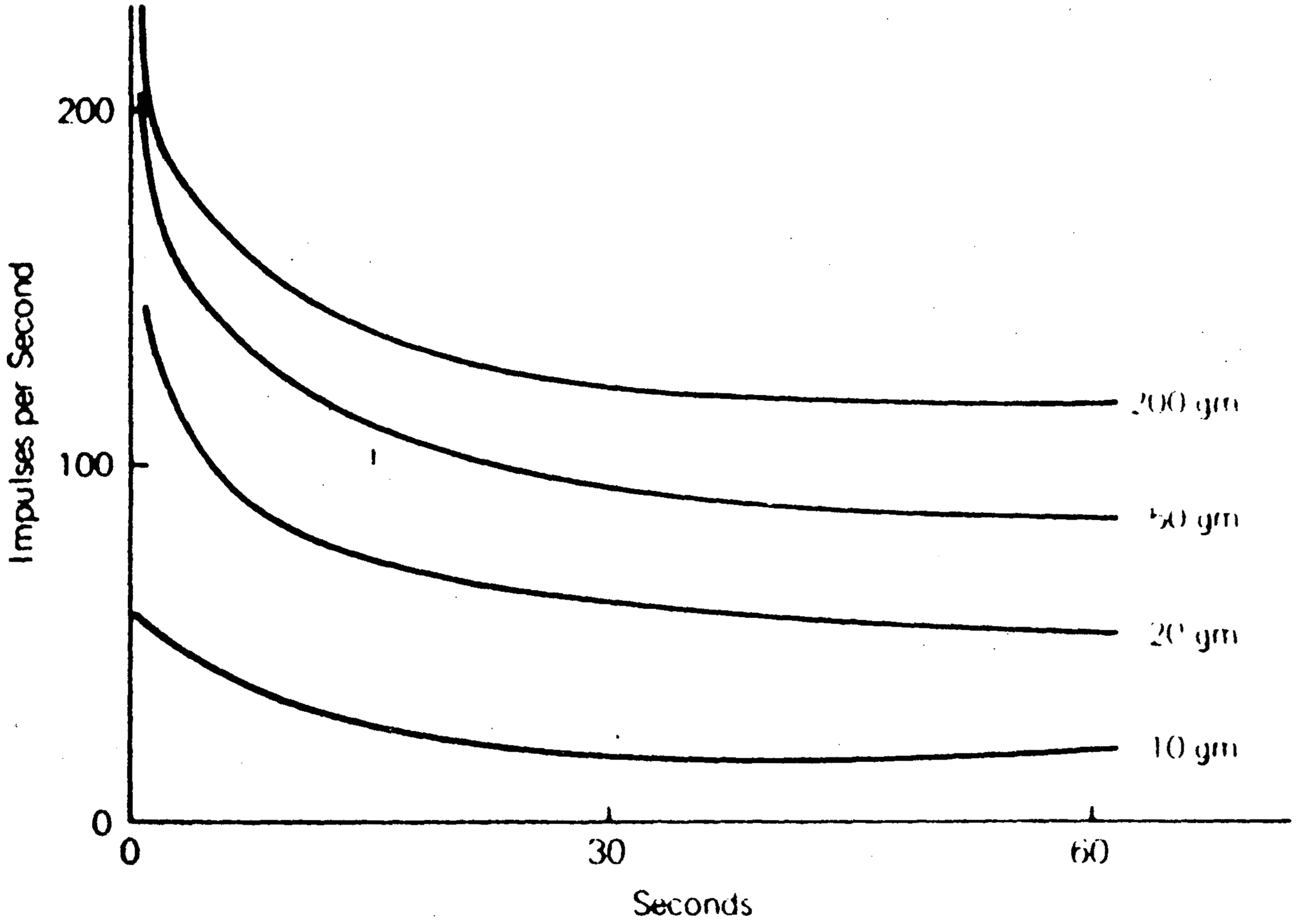


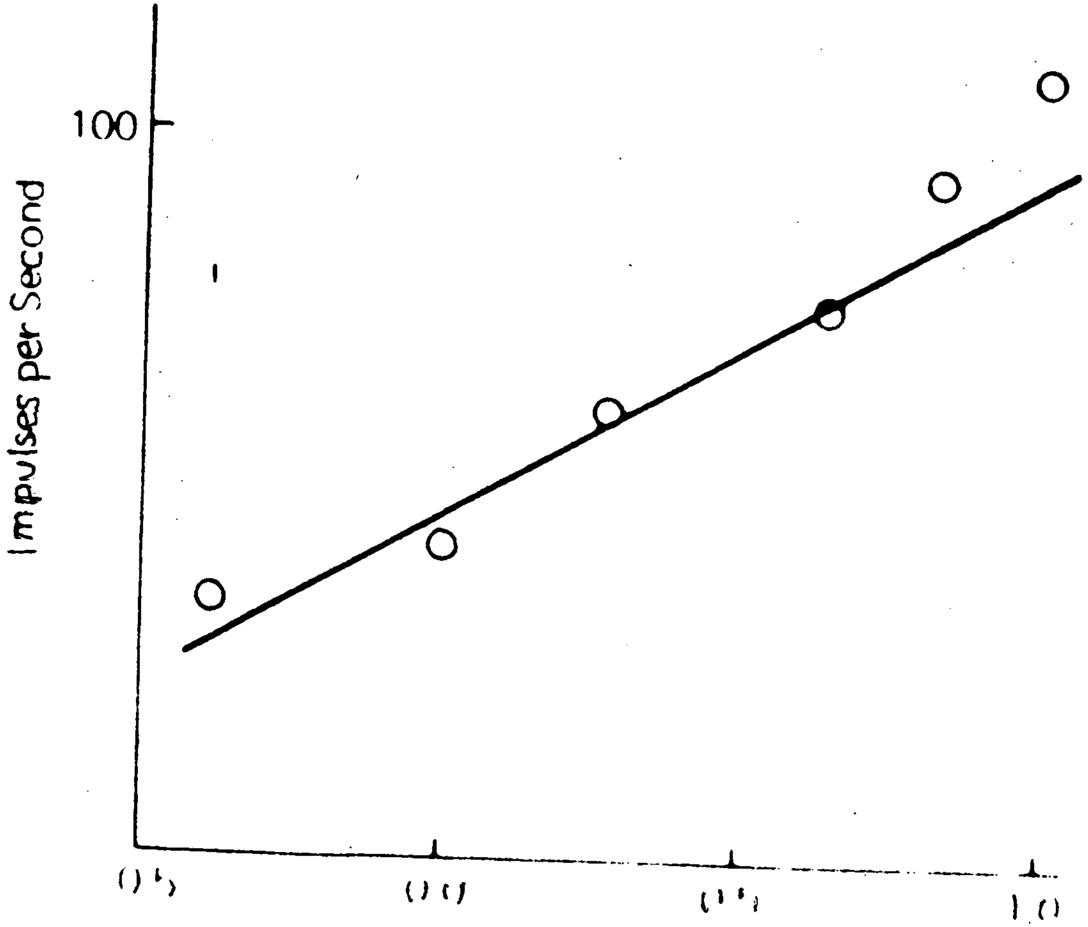
Figure 12: Frequency of impulses in the afferent nerve, plotted against the duration of different loads applied to a muscle-spindle receptor from the frog.

inhibition, between A and B and C, I would be actually be able to discriminate a difference in sensation between a poke received at X and a poke received at Y, even though the nerves that are cabable of sensing that are located almost five times further apart in terms of actual physical location than what they are being asked to resolve. So what that means is that I don't need nearly so many nerves spaced along, say the skin or the back of the retina of the eye in order to get a particular resolution. That's why when you are flying along in your airplane, you're able to see a telephone wire at a distance which is almost 10 times what the physical optical resolution of your eye is in terms of its lens. That's because of that contrast enhancement circuitry.

Now, what I wanted to show here is a typical way that a nerve responds to an input stimulus (Figure 12, frequency of impulses in the afferent nerves, plotted against the duration of different loads applied to a muscle-spindle receptor). Notice that initially it rises up; it initially rises up and then gradually adapts out to some lower level, not always zero; in fact, usually not zero. Another thing then that we have to talk about: adaptation. Every nerve in our body adapts, if only because you pump in so much sodium you overwhelm that pump and it won't fire anymore and you have to wait until you can get some of the chemistry re-established. That means that we really only sense change. You never sense anything that is constant because we adapt to the constant. So we are only interested in change. It is true, as Grant McNaughton pointed out this morning, the human organism is a pattern recognizer. Qualify that; we only recognize patterns of change. And we have a hard time recognizing things that are static in terms of a pattern. You have to force them to change. You say, well I can stare at something for a long time and I'm not moving and it's not moving, but I can still see it. What's actually happening is that your eye has a dither built into it at about 50 hertz and it causes, it will magnify it, but it causes it to dither through a tiny, tiny angle. Enough though that the image is actually shifted to one or two cells on the retina. And in experiments where they have injected procaine into the muscles around the eye, if they clamped the head of the person so that they couldn't move the platform, the people said very rapidly that the whole world looked like they were looking into the inside of a half ping pong ball. And if you tapped a person's head, just that little tiny movement was enough to re-establish the visual world and it adapted out to zero again. All the senses adapt. All the senses only sense change.

And here's the kind of relationship that exists. Another interesting thing, if you look here (Figure 13, frequency of impulses in an afferent nerve, plotted against the logarithm of the load on a muscle spindle stretch receptor), this is the logarithm of the load of one of those cells and this is the number of impulses per second taken off the other drive. From what you see, you see it is a log function. That's one of the relationships. We are capable of sensing change within the environment over many many orders of magnititude. So from the dimmest light we perceive to the brightest that we would normally perceive, there is something like 1012 or 1015. It is a huge, huge, number of orders of magnitude that our sensory apparatus is capable of

Figure 13: Frequency of impulses in an afferent nerve, plotted against the logarithm of the load on a muscle-spindle stretch receptor in the frog. The readings were taken 1 second after application of the load. (After B. H. C. Matthews, 1981)



being aware of and functioning in. And that's one of the things that you have to remember, that this compression, this logarithmic compression is an important thing. When we talk about a change of a factor of 2, in the sound level, that's nothing when you think about what we are capable of perceiving. It's starting to get down just to the limits of our perception. So our perceptual experiences occur over an enormously broad range of stimuli.

There's another thing we have to be aware of, though, that some of the equipment doesn't work just logarithmically, but it works on a curve rather like this (Figure 14, the impulse frequency 3.5 seconds after the onset of light (lower curve) and the logs of same values (upper line) plotted against the logarithms of the light intensity), and that's a power function. There's a great deal of work going on to differentiate between the different parts of the sensory system. Some of them in other words, work in this logarithmic scale and some of them work on this power scale. What it does mean is that all of them are capable of sensing over an enormously wide range of input stimuli.

Now let's get a little more to the topic we have been talking about, the ones that are interesting us in this conference. We are going to start with vision. Here is a cross-sectional view of a human eyeball. (Figure 15, a cross-section through the human eye.) It's got a lens in here which is attached to muscles. There are two kinds of muscles. One of them goes like the tire around your bicycle wheel. When it contracts it squishes the lens and increases the curvature here, allowing you to focus on things that are nearer. There is another set of muscles which are like the relationship between the spokes of the wheel and the hub of the bicycle wheel. They pull the hub open. And so when those ones pull, they flatten the lens and that allows us to see near and far with the same lens. When you go to your ophthalmologist and say, "Gee Doc, I just can't see this close any more when I read the newspaper;" he says, "That's because the lens here has gone all hard on you." Relatively it has gone hard, relative to the strength of the muscles, but we have spent all our lives reading at this distance and the muscles aren't getting the exercise they need, and what happens is that they get flaccid, they become unable to move that bag of lens easily. Including myself, I have taken a lot of people now and got them to do eye exercises, near-far, near-far, 5-10 minutes a day, re-exercise these muscles with visual pushups and what happens is that they get their vision back in terms of their ability to accommodate. So it's a very flexible system. Marvelous thing the eyeball. What that lens is doing is that it focuses light onto this retina which is a whole bunch of nerve cells, again specialized to receive light.

Now, what does our retina look like? (Fig 16, the connections of a few typical cells in the retina) What it looks like is this--you've got receptors in here--remember early lessons of cones and rods, well that's just from the shape of them. These cones, they are sensitive to colors and bright lights. The rods are sensitive not to color but to very dim light, and actually that's the back at the top. The lower part of this slide shows all the nerves that

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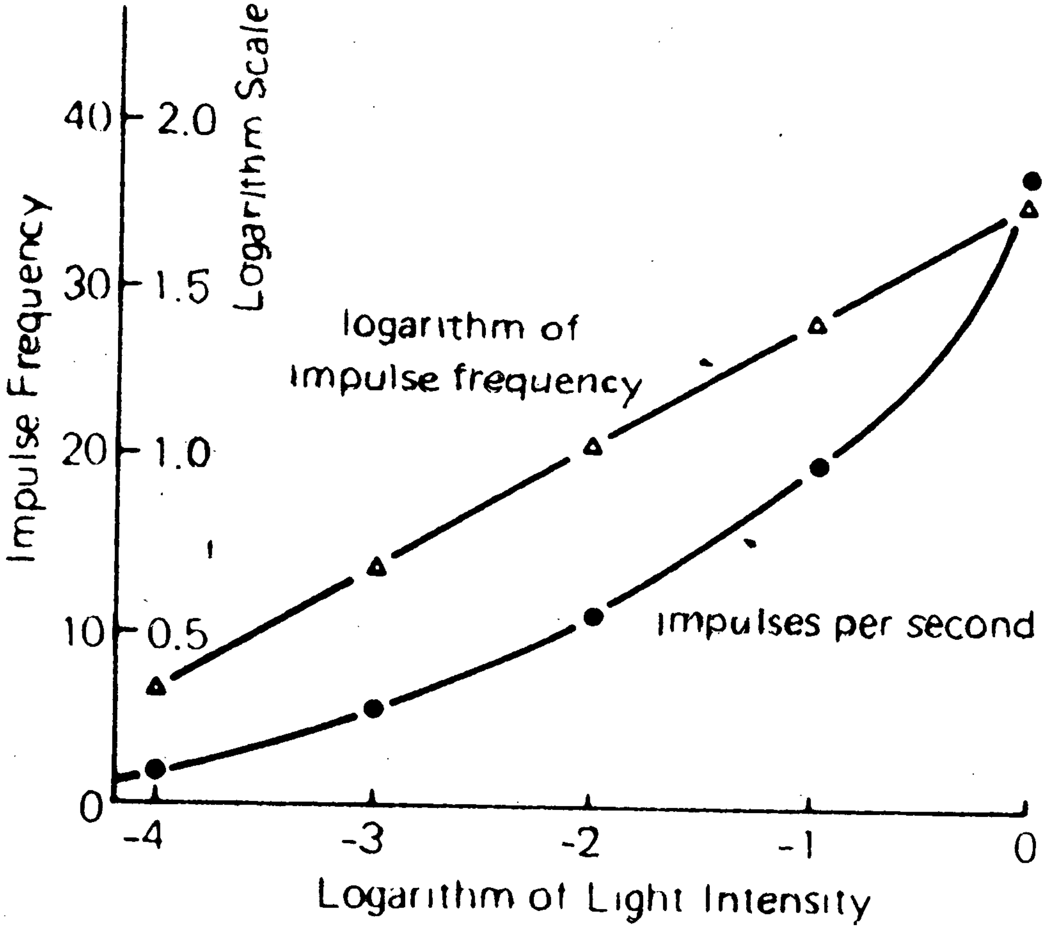
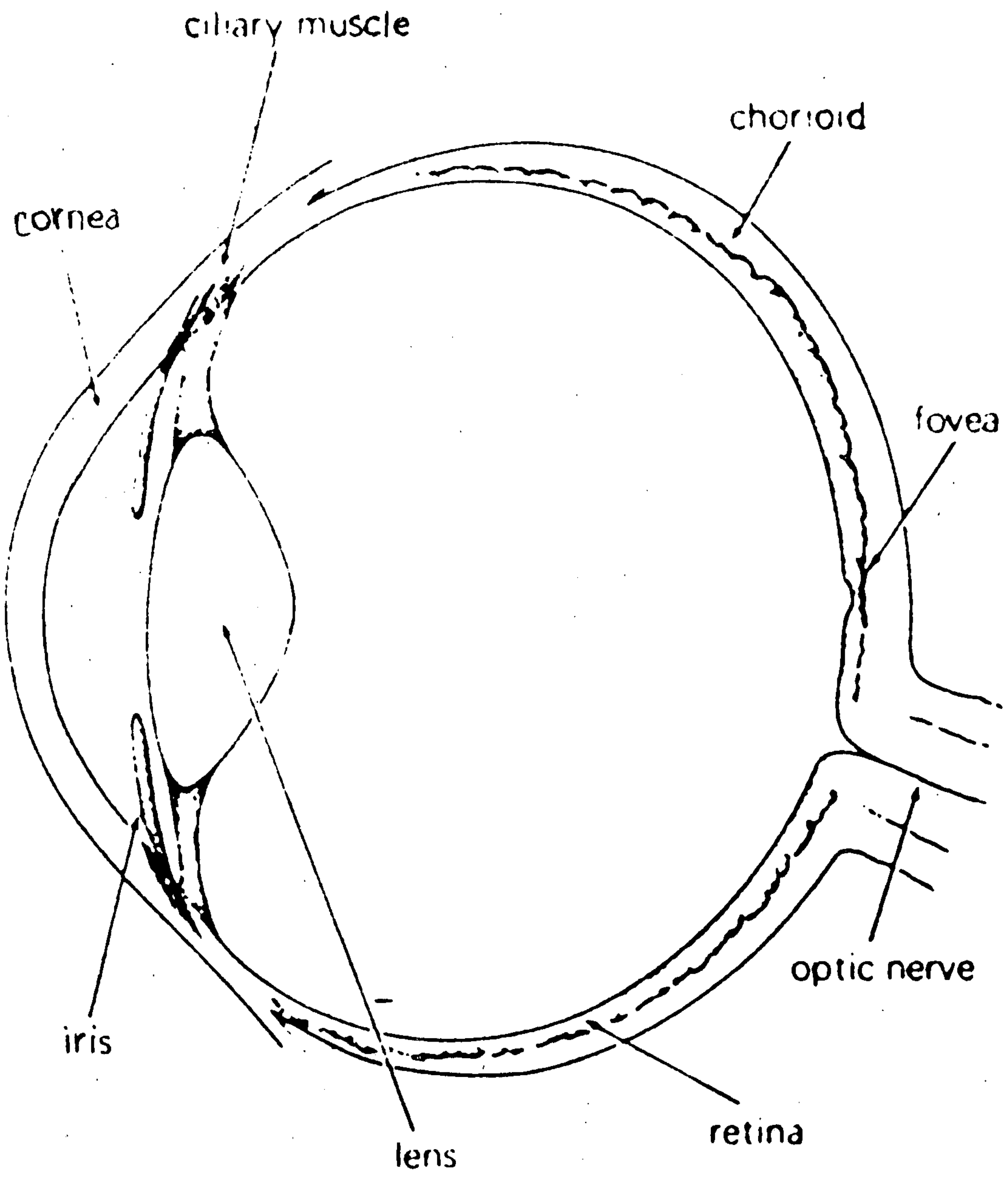


Figure 14: The impulse frequency 3.5 seconds after the onset of light (dots) and the logarithms of the same values (triangles) plotted against the logarithms of the light intensity in arbitrary units. (After Hartline & Graham, 1932.)

Figure 15: A cross section through the human eye.



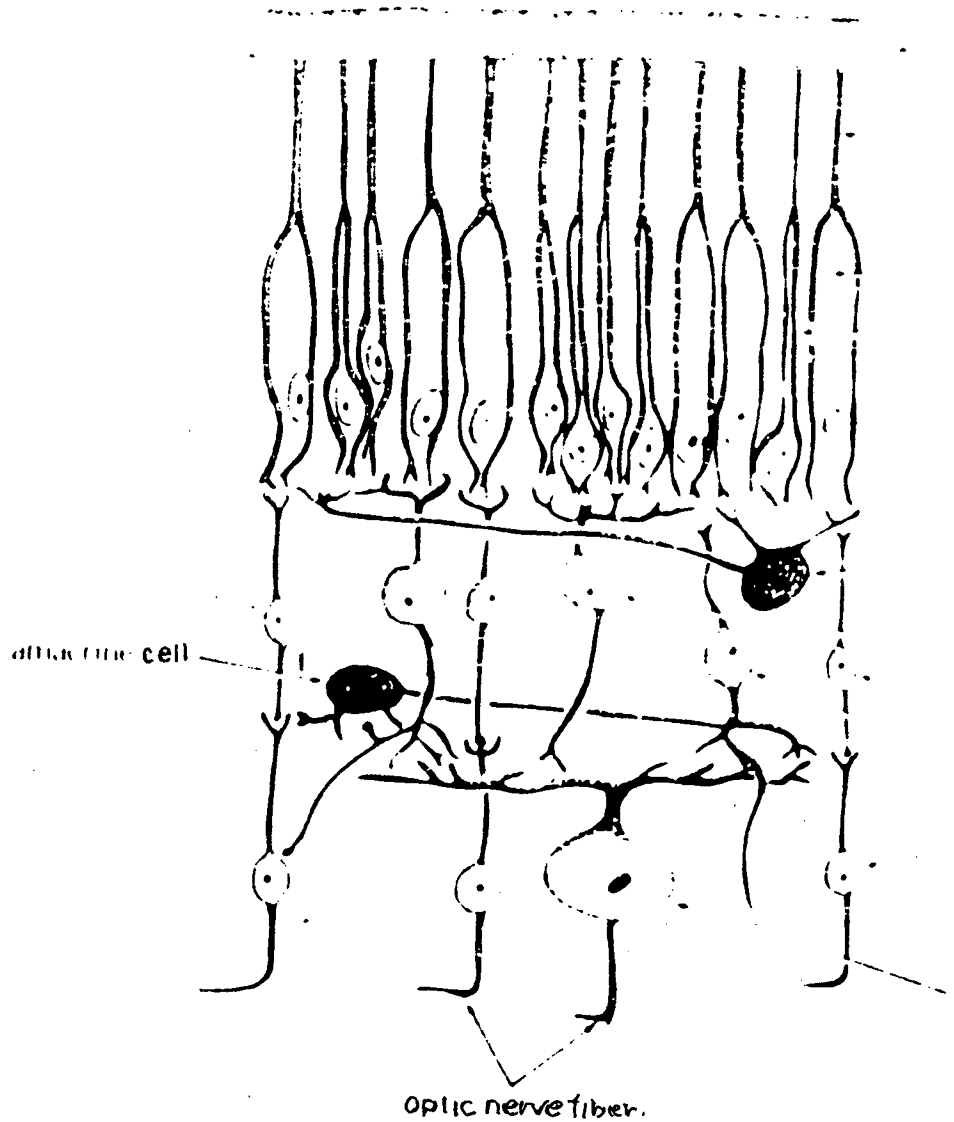


Figure 16: The connections of a few typical cells in the retina. Light must pass through the inner layers (at the bottom of the figure) before reaching the light-sensitive outer segments of the rods and cones. Neural activity travels in the opposite direction toward the optic nerve fibers (After Polyak, 1941; Everett, 1965.)

it connect with it in the front and the light comes from the bottom of this picture, shines through all these very clear looking cells which are transparent and excites these rods and cones into producing electrical changes which are then sensed by this middle row of bipolar cells here. The electrical changes actually kind of get summed up on this row of cells here, and they, in turn, release chemical onto these big fat ganglion cells at the bottom of the picture, which then start to carry the information into the brain. There are other cells along here in the middle layer and they're associated in part with this collateral inhabition we talked about earlier on. So again, there's sharpening of the image right at the sensor itself and already it's processing because you can see that the number of connections that these bottom row cells make compared to the number of connections these middle row cells make is very different. And that's why, for instance, you can generally only see big objects out here in the periphery as opposed to really tiny little fine points in the central part, and that's because of the ratio of interconnections that it makes with the sensing cells, depending upon where it is on the retina of the eye.

Now, what I want to show here (Fig 17, pathways of the mammalian visual system) is again the richness of signal conversion or signal enhancement as we move from the eyes over there to the left of the picture. You notice that, say the left field of the eyes all go one way; first of all the image is flipped over so the left visual field now appears in the upper part of the retinae and they come over the upper circuit of this picture (the right side of the brain) and the right part comes around the lower (left) side. Never mind all the names of these things. This middle part (pre-tectal nuclei) here is associated with that focusing that I was telling you about. This part here (superior colliculi) is associated with directing your gaze; you see something that you want to look at, that's the mechanism that allows you to move the eye in that direction. And this part here (lateral geniculate nucleus) is associated with actually presenting an image onto the calarine cortex of the brain at the very back of the skull which is thought to be a map of what's out there--it's a kind of an electrical excitation map spread out. It's distorted but nevertheless spread out on the surface of the brain at the back of the skull.

Now, we talked about the cones earlier on, and what you notice is that this is a spectral sensitivity of those cones (Fig 18, absorption curves for the outer segments of three types of cones in primate retina). So the part I want to mention here is you notice that it is not a sharp line. You notice that the receptors that see blue (left-most curve), in this case actually extend into the field that all the others do; and so this one (in the middle) sees yellow; this one (on the right) sees red. There's a lot of overlap, and that contrast enhancement starts to refine what you see. But it's because of that overlap that we are capable of seeing hues of color--we don't just see primary red, primary yellow, primary blue--we can see all kinds of color in between that rainbow. One of the reasons is that the receptors are capable of overlapping and then we use a neurological enhancement in order to find what

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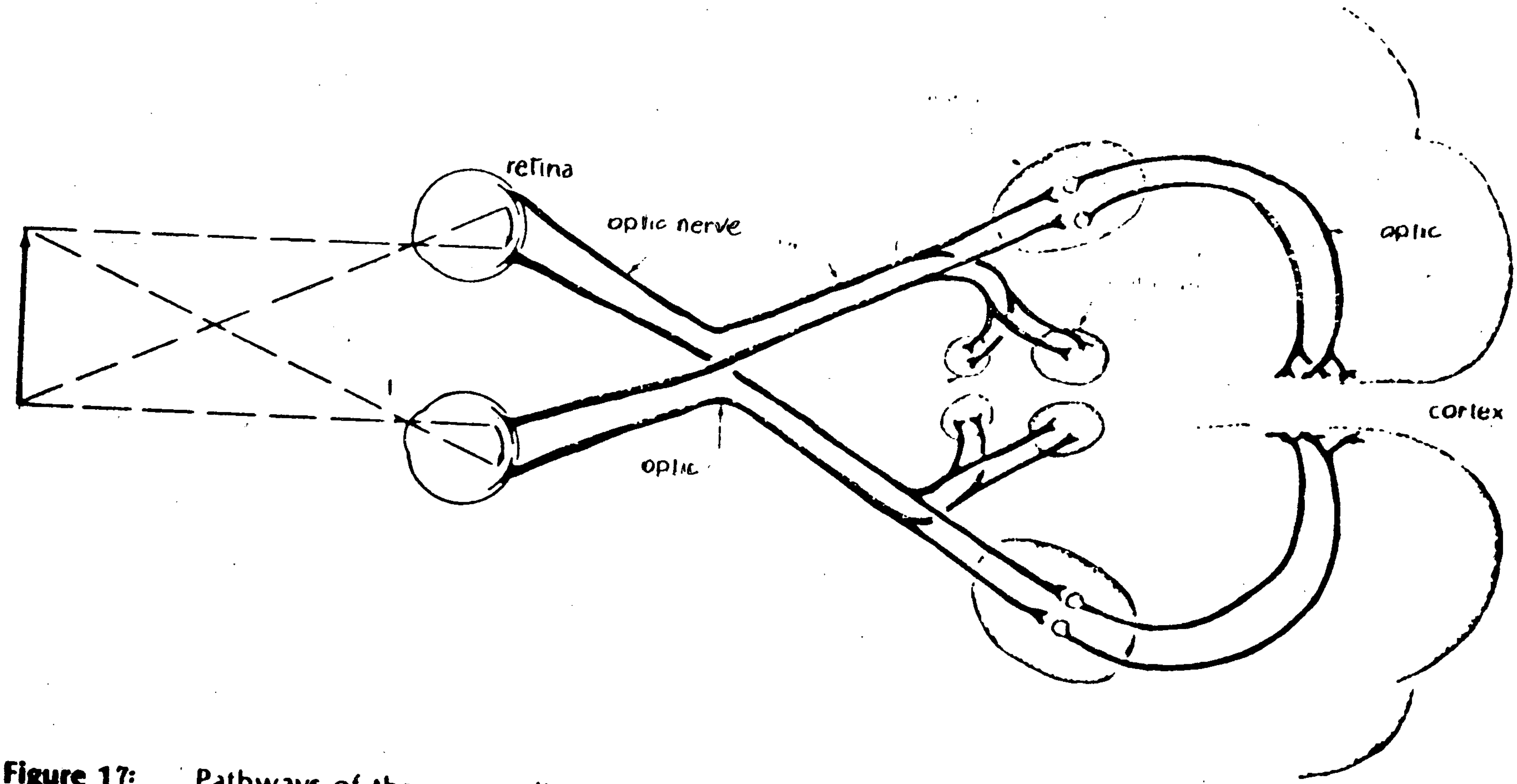
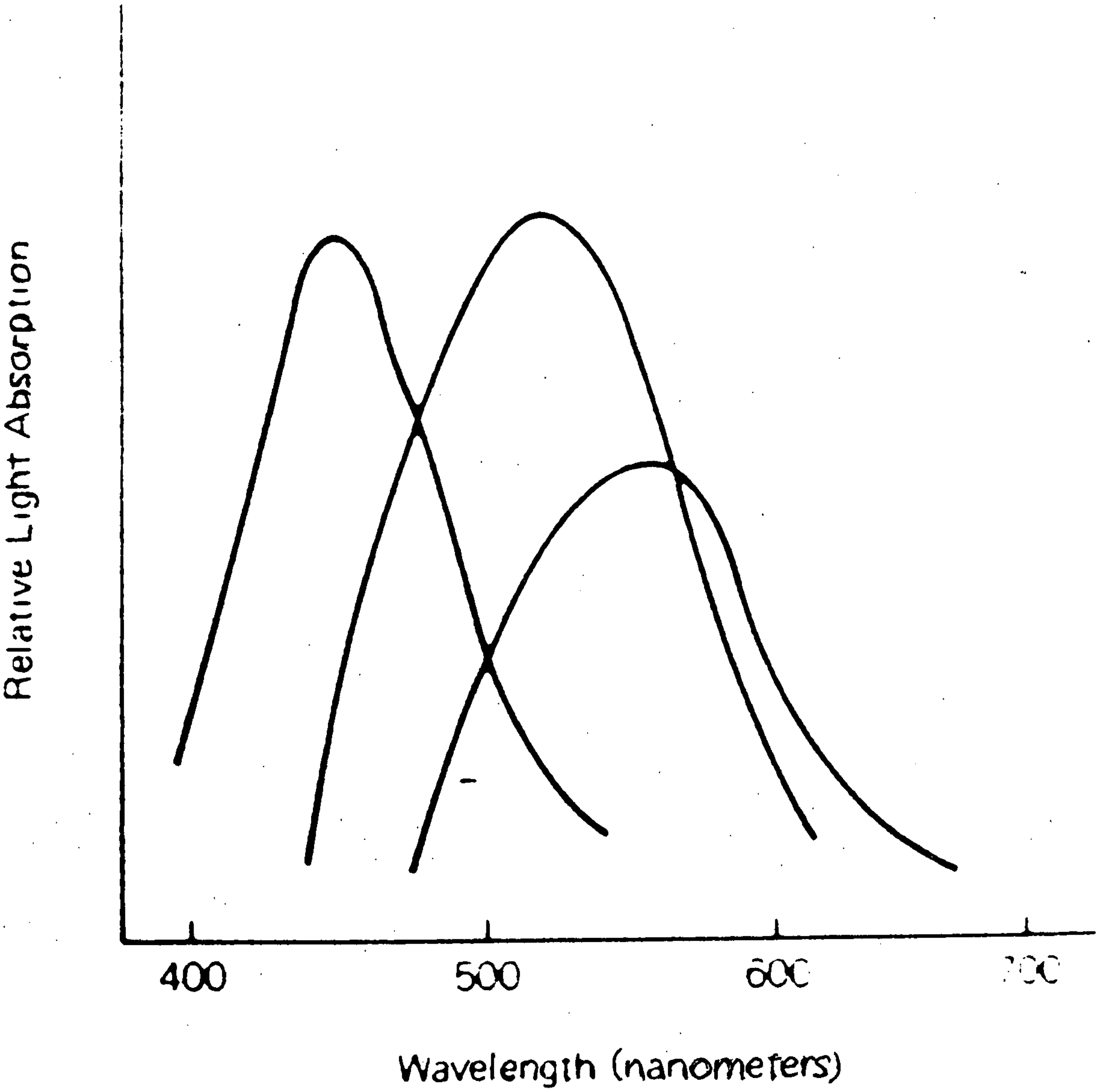


Figure 17: Pathways of the mammalian visual system.

Figure 18: Absorption curves for the outer segments of three types of cones in primate retina (Data from Marks, Dobelle & MacNichol, 1964; Brown & Wald, 1964)

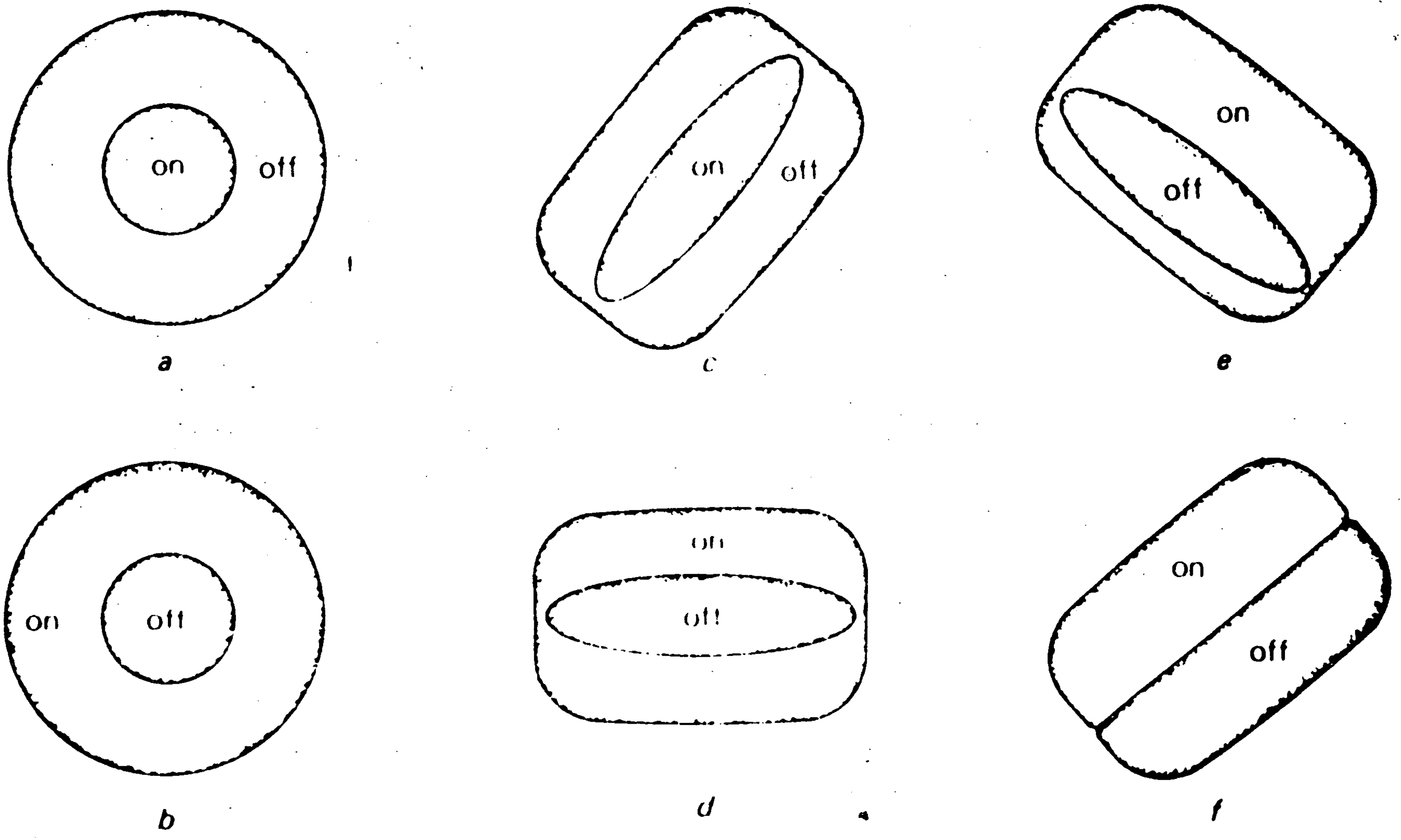


the exact hue is between the center lines of each of these receptors. Again, richness of experience.

When we get back now into this area far back in the skull (Fig 19, arrangement of visual fields), what you find is that there are areas of activity. Noting Fig 19 a and b, if I get a little pinpoint of light on the cell in the retina, somewhere back in the cortex, you'll see a pinpoint where a bunch of cells or maybe only one cell or hue would turn on and the neighbors would be inhibited. And the color of this is also true, some of them would turn off and there would be a pattern of neighbors that are excited. A long time ago now, it was discovered that the same also was true for lines, (Fig 19 c and d) if there is a line out in that visual representation, there'll be a group of cells that will fire in response to the line but only in a certain orientation. If you change the orientation of the line, (Fig 19 e and f), a different group of cells. And, it goes on farther than that; if a line now moves in one particular direction, one group or one cell will fire and if you change the direction of movement, it shuts up and another one takes over. So we're starting there to see that what the brain is synthesizing out of all that information that comes onto the retina of the eye is particular qualities that it is interested in. In this case, lines or spots or velocities. Other ones are angularities, roundness, size. All right, is it a fine detail I'm looking at or a big detail, and so forth. All of these different features are extracted out of that information that comes onto the retina and they become the internal representation within the brain, the language, the words with which the brain uses to describe the experience at the moment.

We're gonna switch for a minute and we're going to talk about hearing. We don't have enough time to dwell on any of it long enough. Here is (Fig 20, the middle and inner ear) somebody's outer ear is out here (to the left side of the diagram). In other words, I'm looking at you on this diagram here. Now what happens is that here's a semicircular canal at the upper right, the things that make us dizzy or they don't; there is the eardrum. The normal ear uses a spiral, the so-called cochlea, but in this diagram it's been straightened out, because it's actually a tiny structure, only about an inch long, and inside of it is a membrane. It's anchored all the way around the sides and there are nerves, about 20,000 sets of nerves, all along the distance here. The sound pressure causes this eardrum to move. First of all it changes things which are impedance matching devices, that's like the bell in a horn. You know when you go to blow a trumpet, you start out with a sound of (puckered kiss) and what comes out is that beautiful note, and that's because it was through an impedance matching device, which is the exponential horn on the end of the trumpet, and couples it out to the room. The same thing here, the air is a big excursion of a very light material and you've got to couple it to the water that's in the cochlea here, so you go through this 40 to one reduction in terms of leverage (pointing to the ossicular chain), and now you get a standing wave which is set up in the water. The water gets pumped along the top and down along the back and through this flexible membrane, which I'll show here (Figure 21, traveling waves in membranes

Figure 19: Arrangements of visual fields. (a, b) Fields of geniculate cells. (c, d, e, f) Various types of cortical-neuron field. Each type of cell has many orientations. (After Hubel & Wiesel, 1962.)



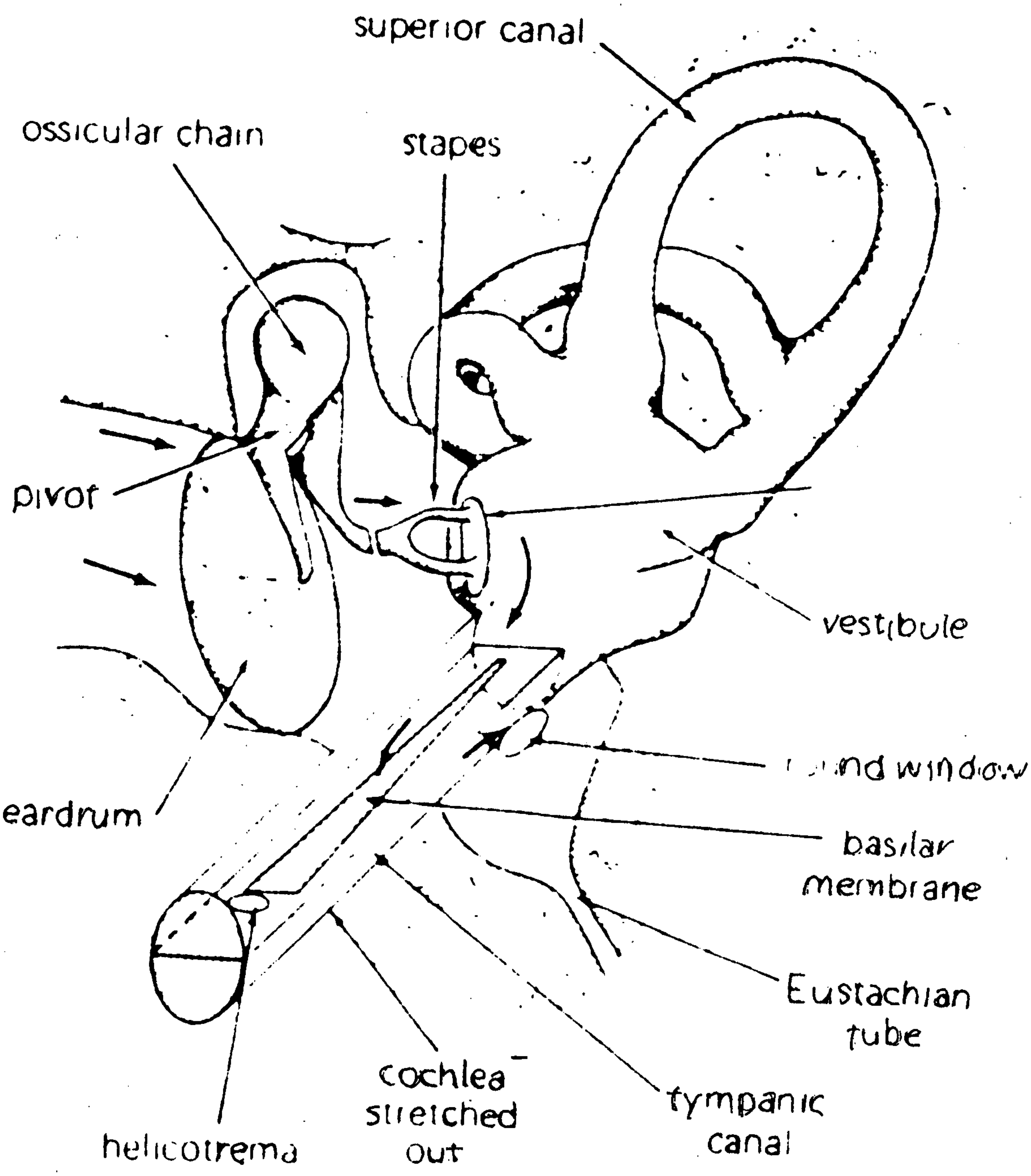
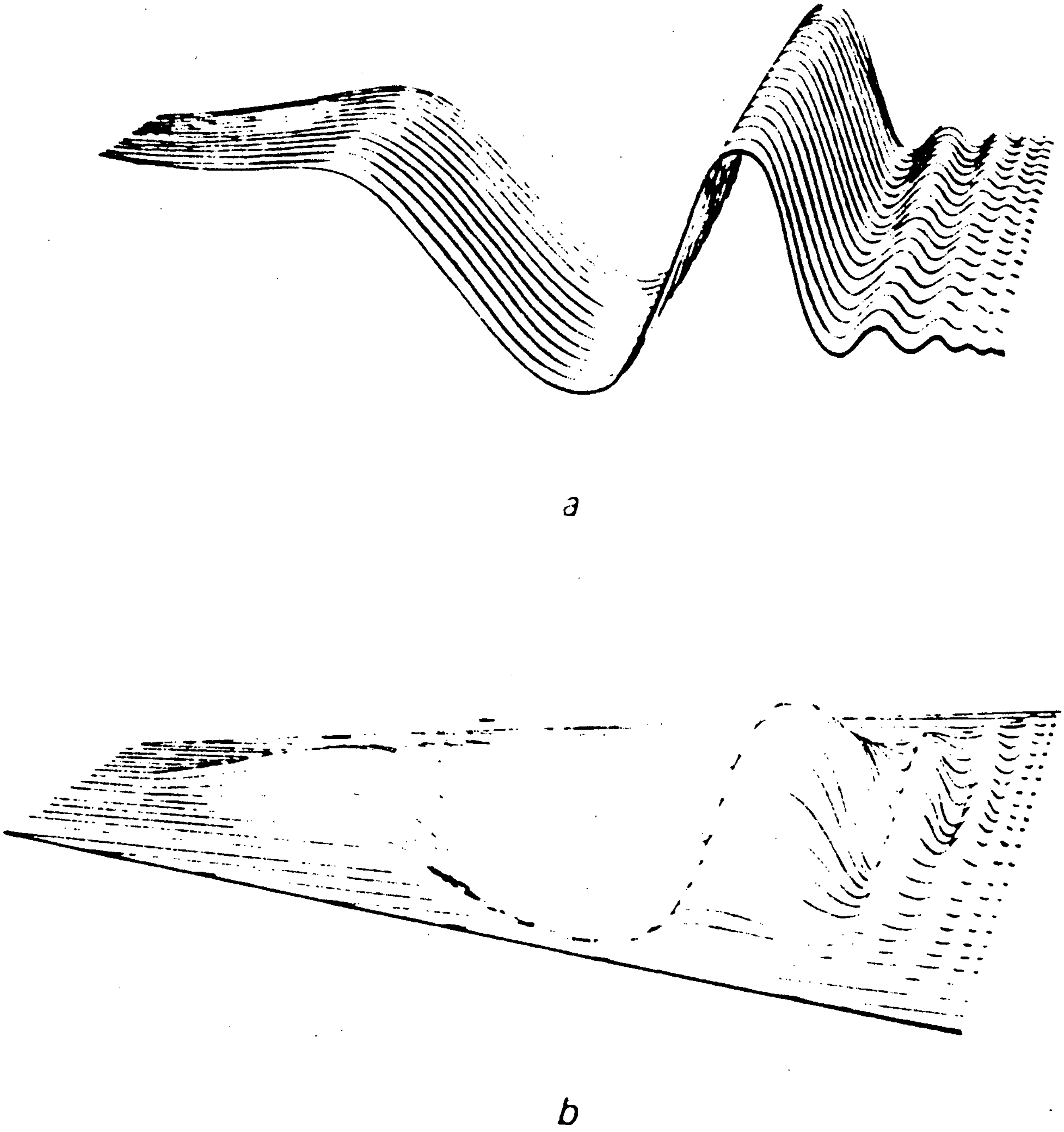


Figure 20: The middle and inner ear showing the cochlea uncoiled. The basilar membrane is wider at the apex than at the base of the cochlea. (From Békésy, 1962.)

unsupported at edges and in a membrane similar to the basilar, in which edges are fixed). You can see that it causes a kind of wavy action in the membrane. Remember I told you the sides of the membrane were anchored as well as the ends, so the kind of wavy action that you get is represented here, a high degree of excitation and then it settles down again. So that's going to tell the nerves here and here (Convex bulges on Figure 21 b) that the frequencies it's hearing are, say, in the middle of your experience. Because it's actually standing where this gets set up, this had physicists confused for a long time. Physicists would say where the speed of sound and water is so great that if you were going to set up a standing wave, it'd be something 30-40 feet long, but it's an interference device. Remember I said that on this membrane, the sound pressure first went in through the top and then back along along the bottom, and it's the difference between the two that is actually measured, the interference between the two that displaces this membrane at any one instant. And the nerves are arranged along the membrane in a row and they sense the movement of the membrane and convert that into an electrical energy. But the trick that nature used in this case is it has traded the big amplitude of movement into something that is actually very fine. It turns out that at threshold you are capable of actually barely sensing the movement of the water molecules due to their temperature. That's how sensitive the little nerves are there that sense that, so nature has invented a very sensitive mechanical transducer and that means that the movement here, because it's an interference or the difference between an incoming and a reflected signal, even though it's very tiny, the brain is capable of getting a message which is then proportional to the tone. And it turns out that for very low frequencies, the oscillation has the time to get all the way down the end of this membrane and excite this end (right end of Fig 21 b) before it can reflect back and cancel itself out. Very high frequencies, 20 kilohertz or so appear to get shorted out through here and the rest of the membrane remains silent. So what happens is that very high frequencies excite only the narrow ends and rigid stiff end of the membrane (left end of Fig 21 b); and very low frequencies only excite the very low end down here (right end of Fig 21b), and so what the brain gets is a signal that says, "In this case, I'm getting excitation from somewhere right around here." (indicating concavity in middle of Fig 21 b). That's worth about 8,000 cycles per second_ But if you got a signal from those which are demonstrated down here (indicating peak of left-most convexity, Fig 21 b), we'd say that's a 4,000-cycle per second tone. So right away you don't actually hear the music as such, what you're getting is a signal which is proportional to how loud it is and where it came from. And the where tells you what the pitch is. And right away at the end organ you see several things have happened, we've converted energy, there's a contrast enhancement which allows us to refine very closely where it is from an otherwise sloppy device, and it turns out they were capable of discriminating between a large range of tones. We can discriminate down to just a few percent change in the tonality of the note, if you've got really good hearing. That's a very efficient mechanism.

Figure 21: Traveling waves (a) in a membrane unsupported at the edges and (b) in a membrane similar to the basilar membrane, in which the edges are fixed (From Tonndorf, 1960.)

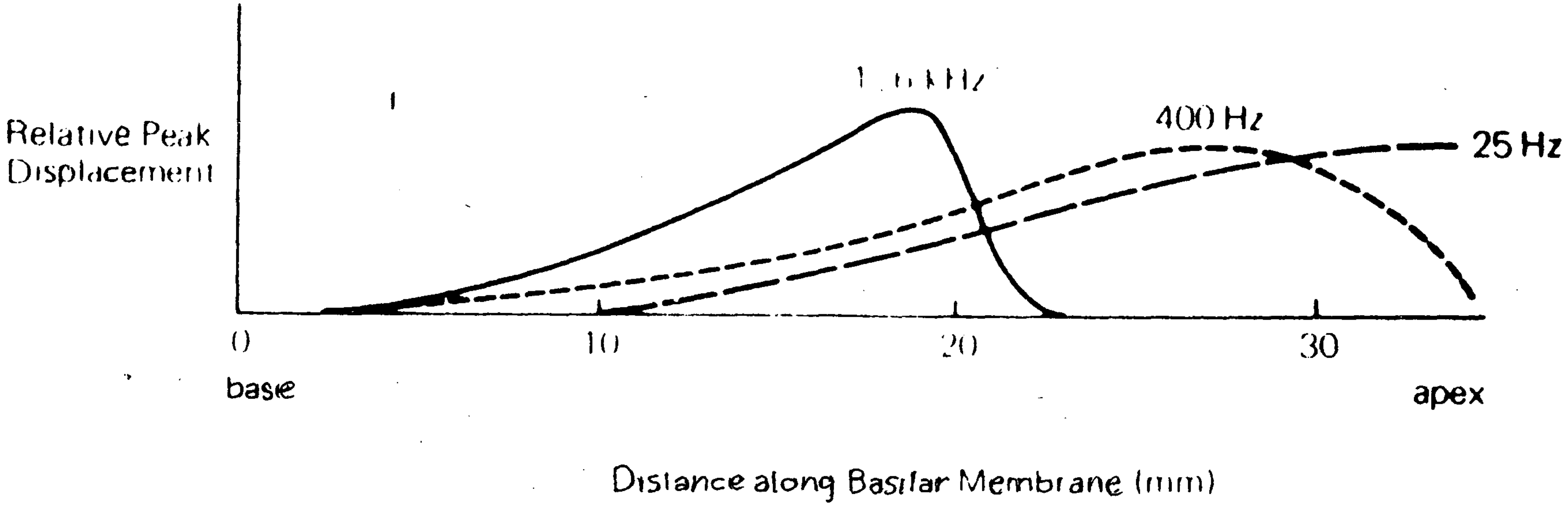


Now this (Fig 22, amplitude of peak displacements of the basilar membrane at different disturbances from the oval window) is just a map of where those actually occur along that membrane. To give you an idea that again it's a kind of compression; you can see, at about 400 cycles per second, the whole membrane down here is flapping pretty hard and so the brain then says, "well, if I want to get down to 25 just what would I do?" Then what happens is that the whole machinery is flapping and it actually starts to count flaps and the nerves turn on and off in synchrony with the actual displacement of the whole membrane; so there're two systems, right? There's a system which is spatially located for the high frequencies and there's another system that says "when I get down around here (indicating the cross over between the 25 Hz and 400 Hz lines on Fig 22), just like the crossover network in your loud speaker, you now change modes," and the woofers in this case actually comprise all the nerves firing together that give you the true feeling of the sound.

Now, what about sound, what do we do with it? Well here is a voice print (Fig 23, sound spectrogram of the speech sound "dra"). You can see on here the abscissa is the time duration and it starts a half-of-a-second from the origin, and the ordinate here is the frequency at which a particular sound occurred into this machine, and this particular person is saying the sound "dra". Look at all the frequencies that occur in just the sound "dra". The beginning of the sound, the D sound, you see, has a different spectral content a rising portion here like a shift in frequencies and the R sound has a different density of frequency components to it. So that gives you an idea of how rich the information is that's available to the brain.

I'll give you a few other examples. These (Fig 24, simplified spectrograms showing the first two formants only, for a number of syllables) are just outlines of the curves. You can see there's a sound D, Da, Du, Gi, Ga, Gu. Notice each one has a different set of spectral components to it, and that seems to be what it is in the machinery that is discriminated that allows us to hear somebody speaking. What's happening is that the machinery that I've been talking about is so sophisticated that it can pick up at this very rapid rate. Remember we're only dealing at 150 milliseconds there. Entire shifts in the spectral content, the_energy distribution along the frequencies that are impinging on the ear. That's the kind of thing that's going on all the time that you are listening to me right now. So it's a very, very sophisticated mechanism, this hearing system we have. Add to that the fact (and I don't have any illustrations to it right now), but you can perceive what it is, I've got two microphones stuck in here and the brain is capable of sensing the phase angles of a sound. In fact, it turns out that the cells that do that are capable of distinguishing down to about 30 microseconds in differences in timing between your two ears. So that starts to give me the ability to sense the direction at which sound comes from, because I've got a kind of tuned array. If I want I can say that a sound that comes here from this direction impinges on the two ears with different time relationships than the sound which emanates from over there. We add to that further the fact that the thalamus and all the inhibitory mechanisms are all tunable. So what

Figure 22: Amplitude of peak displacements of the basilar membrane at different distances from the oval window. Values for low-, middle-, and fairly high-frequency sound input are shown. The membrane displacements shown on the ordinate are not to the same scale as the length measurements shown on the abscissa. (After Bekesy & Rosenblith, 1951.)



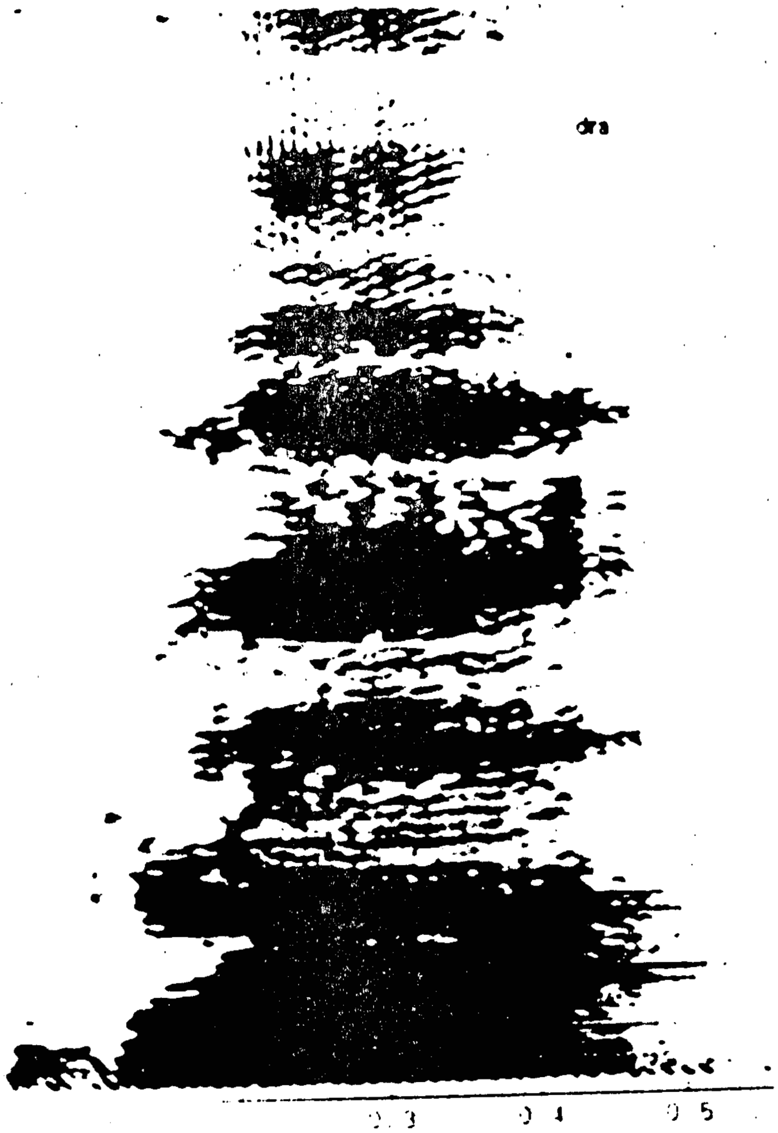


Figure 23:

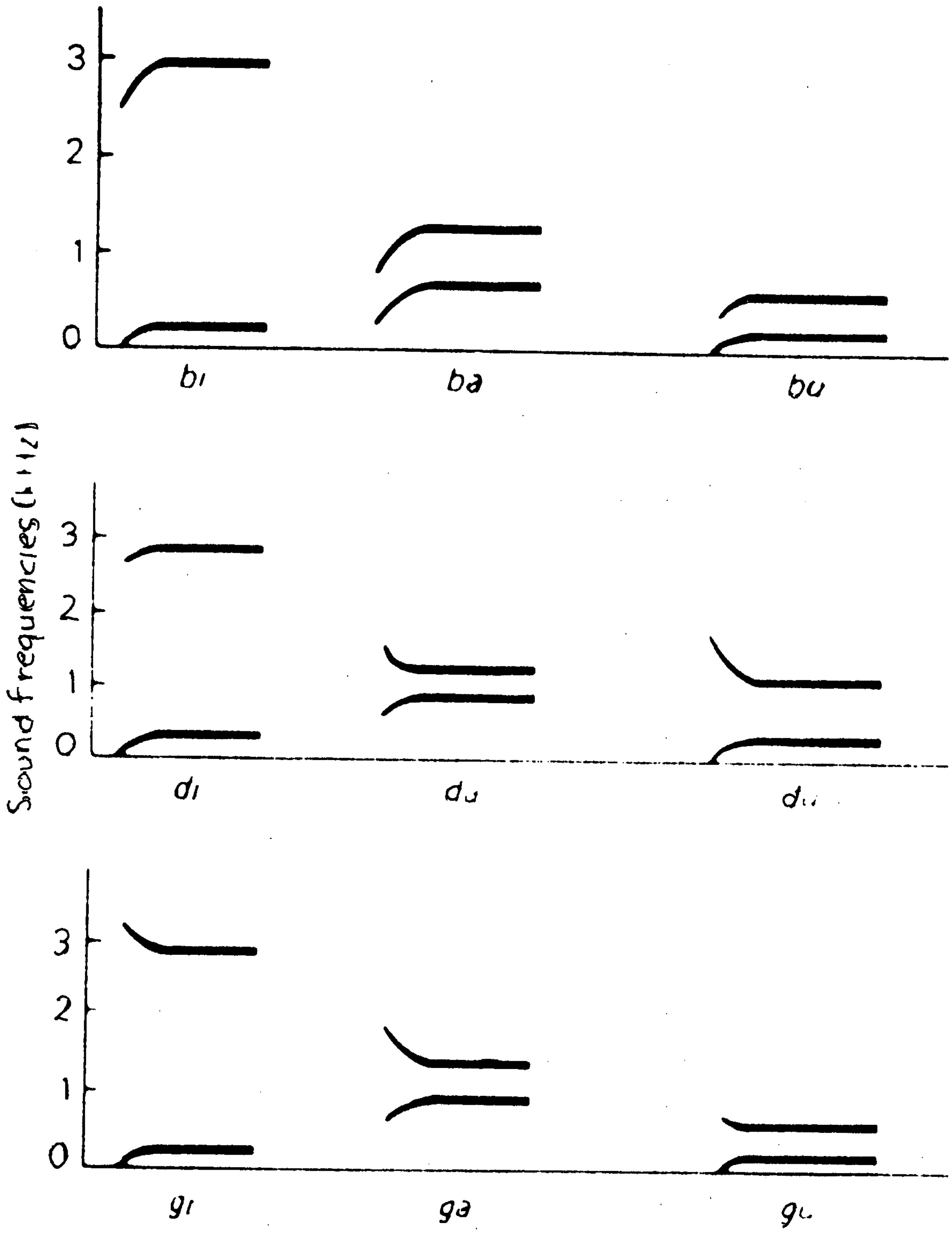


Figure 24:

I can do is I can operate a tunable filter, and that's why I can hear, say, somebody gossiping about me at a cocktail party with a hundred people at it, and I can hear that one voice three couples over, that happens to be what I want to listen to. Because even though they're lost among the ambient noise, I can tune my filter such that I can listen to where they're coming from, because I am able to do this kind of thing actively. I can do it in real time actively and cue on one source as opposed to another. So that's how rich the hearing experience is.

Another thing that I wanted to show you here is that the world is filled with sounds which have that kind of richness to them. If you look at a piano note as opposed to a violin note playing a single tone (Fig 25, wave forms of a violin playing the note G above middle C and of a piano playing C below middle C) while it's split up there, you can see that the violin G is almost like a sine wave; and if I break it up, if I do a Fourier analysis of all the different components of energy as a function of frequency in there (indicating the violin scale), you can see that there's a fundamental tone here, and a second, and ultimately higher harmonics with different amounts of energy in there. That's the amplitude on the ordinate in that scale, this is the frequency along the abscissa. If I listen to a piano where there are many more notes that are all oscillating at the same time when I strike that, you can see first of all that the waveform contains a lot more information (indicating Piano C on Fig 25). Then look down here when you start to look at the composition of that note; all kinds of harmonic information is in there, way way out, and many more frequencies are represented. The brain actually hears that, and that's why when you hear even a single note played for something like a quarter of a second, you can tell that it's not a violin but a piano or vice versa. So that on line, real time filtering system is very sophisticated.

Lastly, I wanted to show a little bit about the organs of balance because that's the other thing we've been talking a lot about this morning and then we'll do so the rest of the conference. What they are, this is a representation of a hollow part of the bone (Fig 26, the bony labyrinth); the inside is hollowed in solid bone, ~~in~~ fact it wasn't until the last 20 years or so that people actually started to get down to the details of how the organs of balance actually did their job. And one of the reasons is that this bone that's in the back of the ear is the hardest bone in the body. It doesn't even have a foamy structure to it, it's just solid bone, and when the histologists would get in there, if they could bore their way into this organ, they would find that the parts which were interesting are the little actual canals which are floating in water inside those tubes. They had the consistency of wet Kleenex, so there was a high probability you'd damage them. So they took about 50 years to figure out how you're gonna get to be able to photograph these things or put them into slides and be able to look at them under the microscope. You can imagine their dismay when they found out that the bits that they were interested in, in here where the nerves come out and which sense the movement of the water in the canals, when they found out that

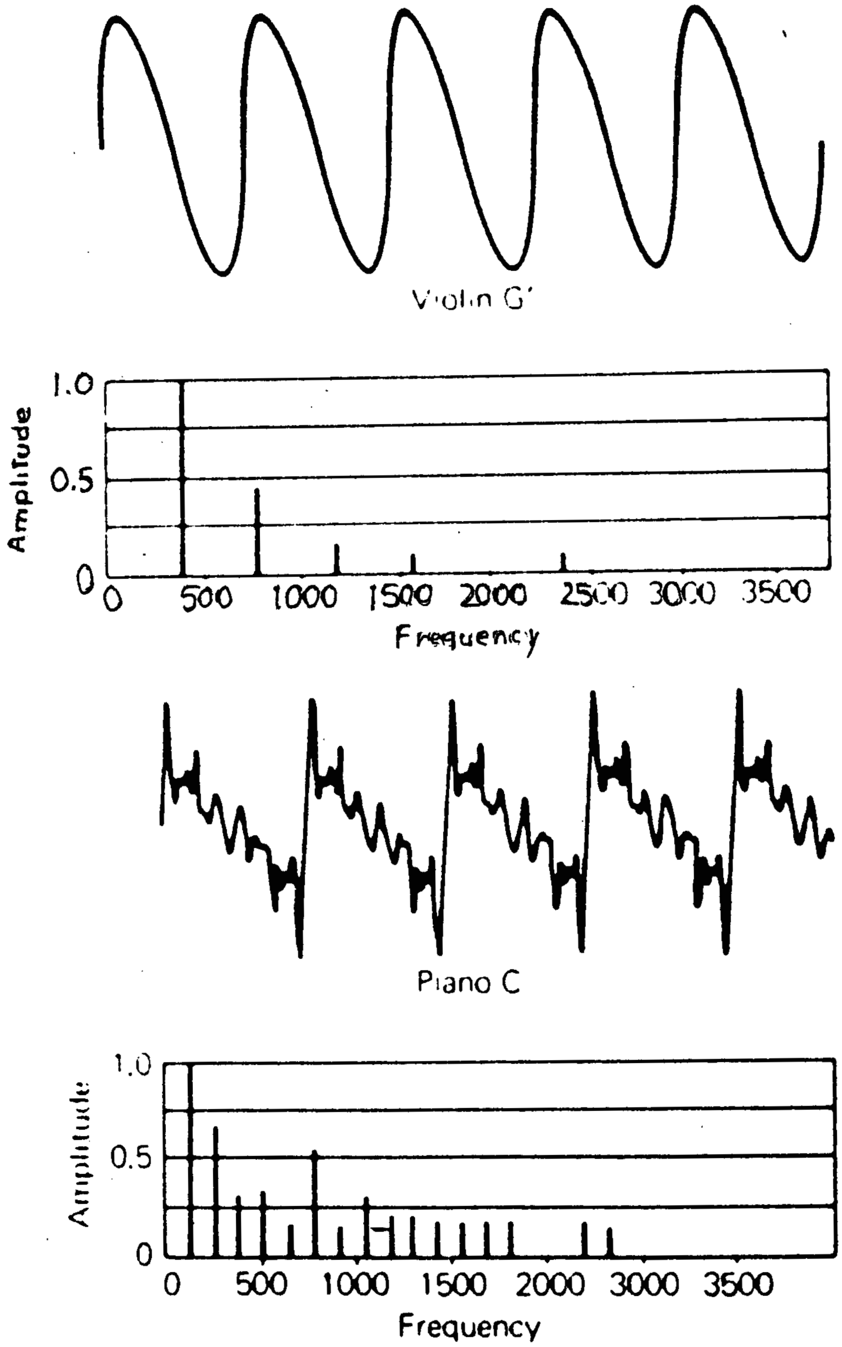


Figure 25: Wave forms of a violin playing the note G above middle C (384 Hz) and of a piano playing C below middle C (128 Hz). The histogram below each curve shows the amount of each harmonic relative to the fundamental note. The richer tone of the piano contains many more harmonics than does the violin tone. (After Fletcher, 1929.)

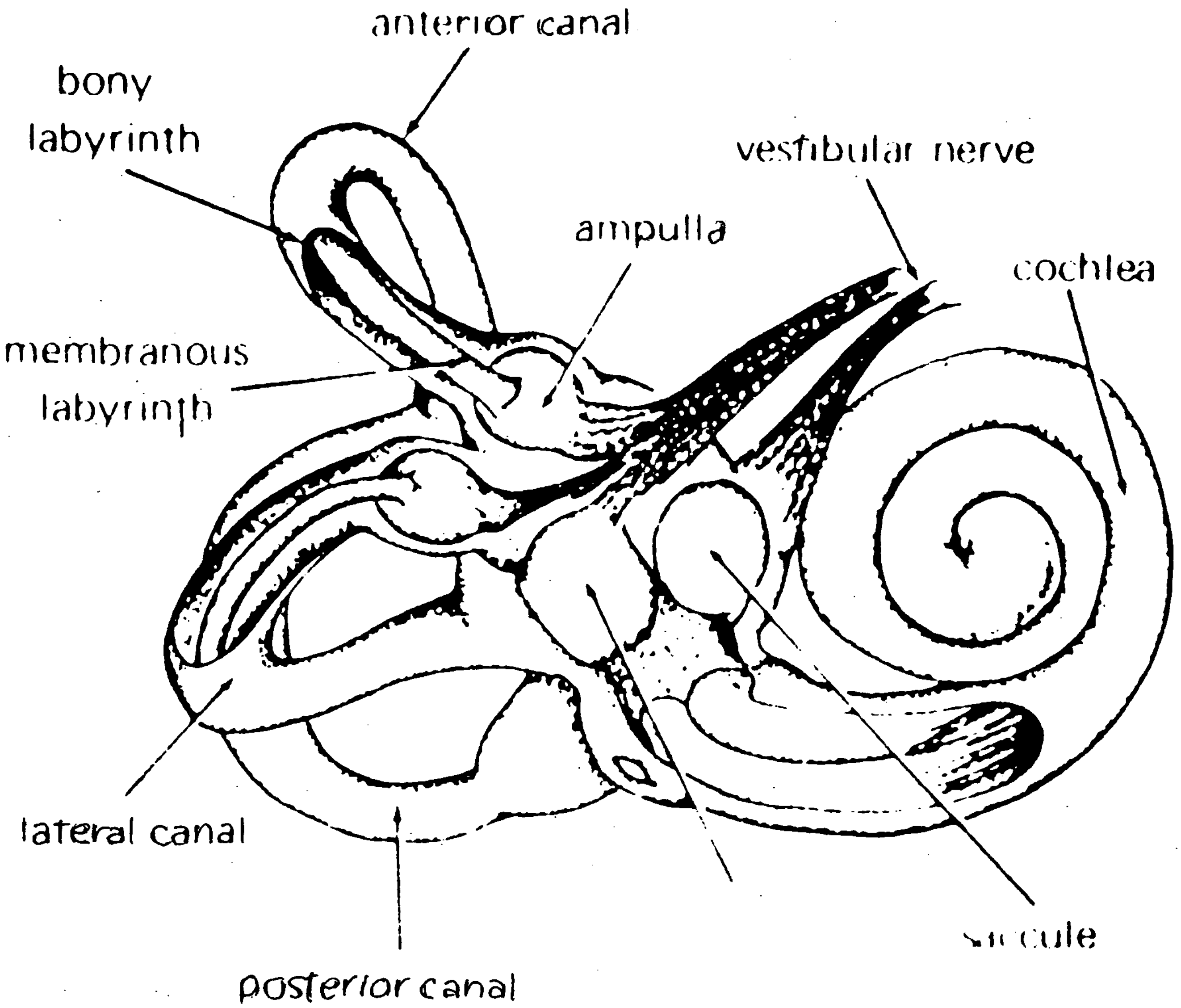

anterior canal
bony labyrinth
vestibular nerve
ampulla
cochlea
membranous labyrinth
lateral canal
posterior canal
saccule

FIGURE 26:

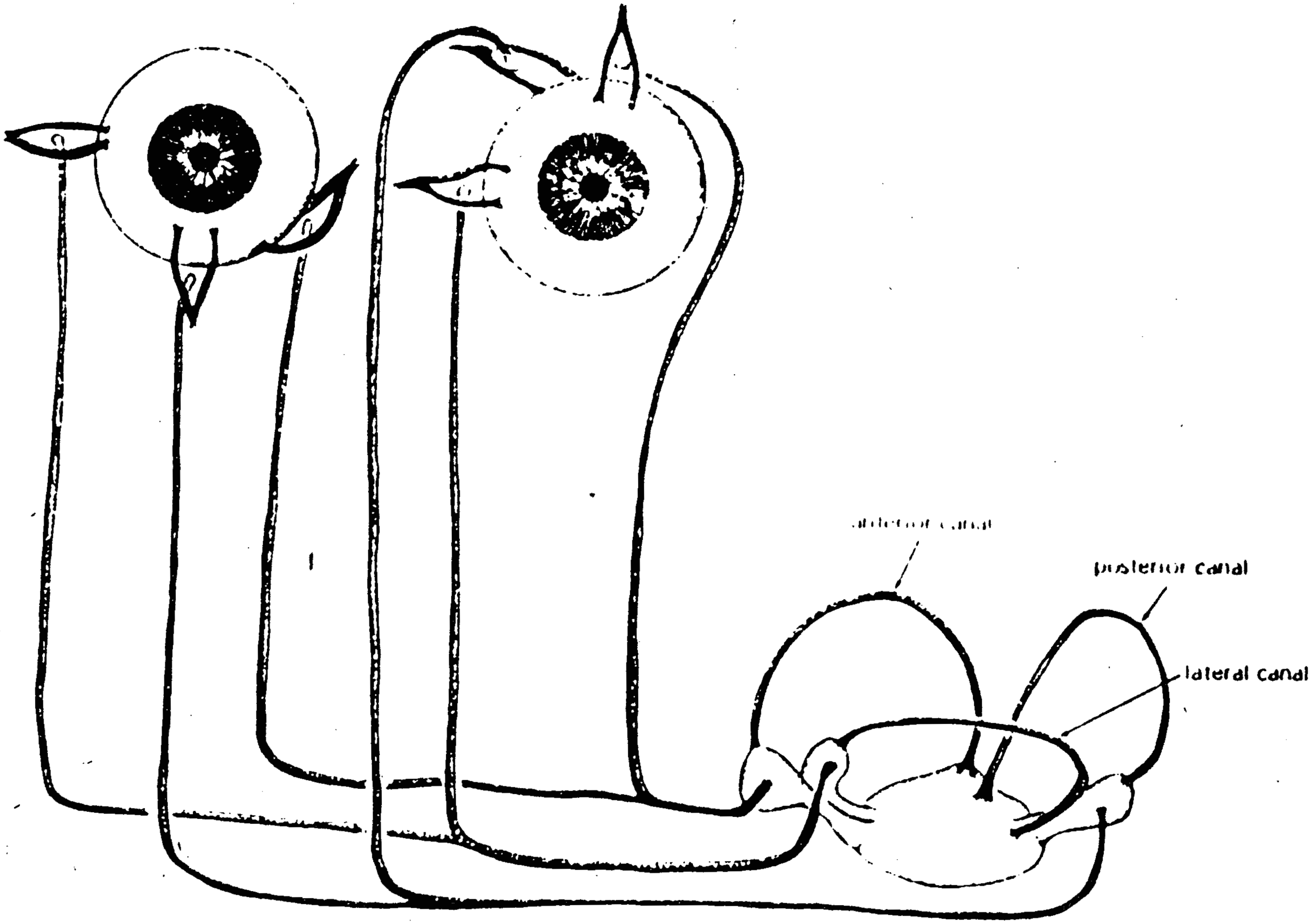


Figure 27 Connections between the ampullae of the three semicircular canals and the extrinsic **muscles of** the eyes. The semicircular canals on the other side of the head make corresponding ipsilateral and **contralateral** connections to the eye muscles. (After Szentagothai, 1950.)

the parts that did the work were actually smaller than the wavelength of light and you couldn't see them under a microscope. We had to wait for details about what these things looked like until the advent of the electron microscope before we could really get a good picture of what was happening here. The part I want you to look at is that these are very tiny. In fact, all this thing that you see here would fit very nicely into the loop that's at the end of this wand here (only 4-6mm diameter). And there are two of them, one on each side of the skull. They happen to show us a very similar type of sensing mechanism which is why they're side-by-side with the organs of hearing that we were talking about a few minutes ago. And you'll remember from your basic physiology lectures on the flight line, well what happens is that as I move my skull, the fluids in one or more of these different canals has caused it to stay behind. If you take a cup of water and you put a little tiny floating bit of paper on it, then you turn the cup fast, the paper stays still. That's because the water isn't a solid, it's a liquid, and it takes a long time, you'd have to put it on the record player and then the water in the middle of the cup would start to catch up to the outside of the cup. Well, the same thing happens here. When I turn my head, the fluid stays behind and what it does is to push on a plug that's in that bulge and the pushing of the plug causes these little nerves to fire and send information up to the brain. Now, remember, that's a viscous medium, so already it's a rate sensitive device, it senses only rate. It doesn't sense actual displacement of your head, it senses how fast your head is turning.

One set of information is sent directly from the organs of balance to the muscles that control the eyes. (Fig 27, connections between the ampullae of the three semi-circular canals and the extrinsic muscles of the eyes.) It's very intriguing to discover that the muscles that make the eyes move in this plane are, in fact, exactly lined up with the plane that this canal was in. In this horizontal canal you can see the diagrams coming in connect exactly to the horizontal moving muscles of the eye and so whenever I move my head side to side like this or nodding like this, what actually happens is that velocity information comes directly from the organs of balance to the muscles of the eye and allows me to stare in one direction and move my head.

You can get an idea of how accurate that system is if you do the following. Do this test which we in Canada call the Newfoundland Intelligence Test (laughter). What that consists of is holding up your hands in front of your face like that and I want you to count my fingers now and you're going to tell me how many fingers I've got up, and then you move your hand side to side and all of you say "ah that's not fair;" come on, yes it's fair because what happens is that if you move your hand about that fast, sure you can't count the fingers but the Newfoundlander is smarter than the rest of us, and he says, "Well, Einstein will be the first one to point out to you that motion is a relative thing and if you are holding your head steady and moving the hand, it would be the same kind of angular displacement if you held the hand steady and moved the head, would it not? And you would have to agree that's true. So he "Hold your hand still and I'll move my head," and when you move your head even that fast, you can still see the fingerprints. Why? It really is that those circuits are connected and they are very fast; it's rate information, I get feed-forward information along the muscles of the eye that tell me where to go in advance almost of the head getting there, and so that's automatic, that's much faster than me being able to think where that is going and following it and track it.

That's one of the reasons why disorientation events are so compelling. The reason is that if these gyros (referring to the semi-circular canals) here topple; they send signals up to the eye muscles which cause the eye to flick around and it makes the real world look like it's turning when, and in fact, it's not. But you don't know that until you're able then to find out what's going on and set it right. And that's why disorientation is such a problem, is that it's dealing with systems which normally are always right and very compelling. And when they are not right, then you don't know it, and you want to believe them and the training you have to undergo is to learn not to believe them. And that's the measure of your sophistication. It turns out that there are other signals that come off these and if you close your eyes, you still feel that your head is turning. They go to a different part of the brain, in fact, the part of the brain that seems to be associated with your being able to figure out if I said, "The washrooms are over there to the left", that allows you to know what I mean by that. So, there's a lot of things that come off of there and a lot of information.

I guess what I'd better do, I could go on obviously for two or three days without stopping about this kind of thing and not exhaust the subject, but I'm sure I've raised a lot more questions than you are comfortable with and so out of fairness at this time, I should allow the floor to go to questions.

B/G DeHart: I have one quick question. Don't your eyes overpower disorientation? And why is it that figure skaters don't fall over?

RM: Yes. You're referring, General, to a series of experiments that were done and are very interesting and they're important. Why is it that figure skaters don't fall over, all right, because they produce a tremendous flicking of their eyes in respose to a very high perceived angular velocity. When they spin it's a blurr; that's awesome. What they do is that they slam to a stop and they look for the nearest spotlight, which is very bright, and they focus on that, and you're quite right. What will then happen is that back at that sub-brain level with the thalamus and so forth, you then inhibit the signals that are coming off, so the signals still come off the canals. Although more recent work has shown that some of those inhibitory fibers go right out to the canals and tend to turn the canals off. And so you produce inhibitory information which turns it off at the origin, turns it off at the eye, and reduces the sensitivity out here because you override those muscles with other signals that come from the part of the brain stem that caused you to look at a particular place; so you have that flexibility as well of altering the machinery which is doing the perceiving, and you have to learn how to use it, that's part of the training is to do that. The figure skater usually falls over the first time.

Q: What's the effect of laying off flying for a prolonged period, then trying to regain currency?

RM: You need to temper that with the time course. Experiments that have looked at this business of degradation of neurocircuitry have shown that there can be some very long time courses and it's not as easy as you think. For instance, experiments that have been done with gymnasts who have been told that what they have to do is not to go out on the gym floor and do their routine, but for six months they would imagine themselves doing their routine, would perform with about 80% of the ability of those who actually went out and did it every day. So what that says is that if you are really a blue-suiter and nobody can keep you from thinking about flying, you are going to de-learn a lot slower than the guy who is glad to be out of there and gone. And so, it is not a simple relationship like that. As long as he keeps exercising it, the evidence is that he keeps those circuits intact.

RM: Yes,. . .Okay, that's a very subtle question and it's a good one. The question being, if I may rephrase it in the terminology I have been using, If you visualize something, if you rehearse it in your mind but you don't actually do it, how effective is that for learning how you cope with very difficult and unusual situations that might be difficult to do in an airplane? The problem is this: when you imagine a situation and what you are going to do about that threatening situation, unless you have been exposed to it a number of times and you know what the whole situation, the whole sensory experience is, you usually cue on only a few of the items that are there and you are now learning in a deprived environment. Because every time that you experience the thing, at least the first 100 times you're still learning; (I'm told by people who do this kind of thing, musicians for example who say that they want to rehearse a piece, say, generally that they have to rehearse it 100 times before it feels right and the muscle memory is capable of playing it). Well, the development of that experience and that ability is a compound not only of what they are hearing and what they want to do, but also all the patterns they have to be able to reproduce. When you are talking about, say, recovery from an unusual attitude, and can I do that after having been explained what that is, perceptually you will not have been able to experience the full extent. The first time you experience that you will probably only be able to cue in on one thing because it is such an unusual thing, it is so bizarre, so frightening that you are probably only going to cue on one thing and that will not be enough for you to develop that strategy. So you need a situation where you have learned what the thing is really like, in all its richness. Now that you have a real understanding of that though, then this mental rehearsal becomes useful. So the mental rehearsal is good for the guy who has had the experience in the first place to keep current. But it doesn't seem to be good for learning complex actions the first time off.

RM: Ah, that's a tough one, the role of simulation in instrument training. Well, what I think is, let me just flick at some of the things you raised. Learning how to handle instruments is not only a perceptual experience. It is also a decision making experience, a priority making and organizing experience, it's a reaction experience. So because it is such a varied business that you have to attend to; lots and lots of decisions, none of them life threatening, at least usually not, that's what you are acquiring; the simulator is very good at giving you exposure while you sort all this out for the first time. What it seems difficult at doing, at least it seems very expensive, is to provide the full richness of the experience to you. So unless you are prepared to mimic very carefully what is actually going on in the airplane, there's not just the movement, the sounds, the smells and so forth, it is the terror, and the threat and all these other things that go with it. That's all part of the ambience, and unless you are prepared to mimic all that with all reasonable faithfulness, you are only getting part of the training. So I think what you need to have is a sophisticated blend of the two experiences: simulation for working out the bugs, and the real experiences for learning what the real experience is. So you don't find out suddenly that, Wow, this is so different when it is happening to me in real life when it is not simulated that I can't relate to it anymore, and you're going to be dead. So, it has to be the blend, and I'm not sure that, on a theoretical basis, you could say what that blend is. We are going to have to experiment with it.

Stan Roscoe: Isn't what you meant to say, regarding the inner ear, that it senses changes in rate, or accelerations?

RM: Yes, the signal that comes off is a velocity signal; but, it is an accelerator. Sorry, I can't buy that.

Stan Roscoe: OK, years ago we accelerated people below their threshhold to tremendous speeds and they felt nothing till you stopped them.

RM: Yes. Yes. That part I would agree, because what you have done there is to bump into the adaptation time constant of the individual. So they are adapting out the signal at the same time it should be building up to a velocity. If you are dealing within, say, a tenth of the adaption time constant of the person which is their usual kind of head movement rate, then you will find that the afferent signals from the canals are rate sensitive, not acceleration sensitive.

Q: Could you comment on proprioception other than vestibular?

RM: Proprioception is a catch word. It has to be a catch word because we don't tend to understand all the mechanisms involved. But in part it is the sensation of pressure. We have the different sensors for light pressure, as opposed to deep pressure. We have different sensors for vibration. We have different sensors for pain, when the pressure becomes quite noxious, and they are spread all over the body. And they extend farther. They are not just in the skin. They are in all kinds of things, in fact, there seems to be some sort of sensors in the brain. Right in the brain tissue itself. I also have sensors which are capable of telling me what the angle is of all the joints in my body, and also how fast I am changing that angle. So these are all lumped together into two things: kinesthesis, the sensation of change; and proprioception, which is the sensation of self. That is the meaning of proprioception. What happens, now, is that as we are walking around in the real world, I would say that one part in a million of our experience, even as pilots, is spent under G. The rest of the time we are at one G, except for short little bursts. Now what happens is that we develop patterns of recognition of what is going on appropriate to being in a one G environment. When I sit down, the pressure is right for one G, lying down, touching something, they are all a one G experience. If I now find myself in the situation where I am, say, at six G, the sensors really haven't got a lot of experience with that. And I don't quite know what to make of it. So everybody is going to have a different interpretation about what this means. According to how they dial up the gains in the system: inhibitory and excitatory. And so some people might think, "Oh, God, I am getting pushed down into the seat," other people are thinking that their joints aren't at the angle where they had originally set them. To add to that problem, and I know what you are referring to, some work that I did that seems like ancient history now, showed that the human being is incapable of deciding which way he went if you move him up and down, because your organs of balance have a plane of symmetry in them in which it is perfectly ambiguous. Birds and fishes which move in a three-dimensional environment have a Lagena, which is a little organ that is a vertical accelerometer; but we don't. We sense when we get off that axis. We took them in a helicopter, big helicopter loads of people, up and down one foot and they couldn't sense it. We took them up and down through 400 feet and they still couldn't sense if they were going up or down and they had a 50% probability of getting the direction right. They knew they had moved: why, because the seat of the pants changed pressure. But they couldn't get the direction right and that's all part of it. And so I have watched people in an airplane when the pilot puts in just a little bit of a yo-yo, but they don't know what's going to come out of that. And they say, "What did we do, up-down or down-up?" They guess. So it is an unusual environment for us, it is one that we are not designed to handle, and what we are trying to do is to make some sense out of this big change that occurred, and we do it on the basis of very little training and even less experience.

THE TWO MODES OF PROCESSING VISUAL INFORMATION AND IMPLICATIONS FOR SPATIAL DISORIENTATION

Herschel W. Leibowitz

Pennsylvania State University

BIOGRAPHY

Herschel W. Leibowitz served in the 75th Infantry Division in the European Theater after which he received an undergraduate degree from the University of Pennsylvania and a graduate degree from Columbia University (1951). Upon graduating from Columbia, he taught at the University of Wisconsin until 1960 when he joined the Federal Systems Division of the IBM Corporation. Since 1962, he has been at the Pennsylvania State University and is currently Evan Pugh Professor of Psychology. He has also taught at the Massachusetts Institute of Technology, and the Universities of Maryland, Michigan, and Florida. Post-doctoral fellowships include the University of Munich, the University of Freiburg, and the Center for Advanced Study in the Behavioral Sciences, Stanford University. He has served as a member of the Vision and the Human Factors Committees of the National Research Council and is currently a member of the NRC Working Group on Night Vision and the U.S. Olympic Committee on Visual Performance and Safety.

Consideration of the role of vision in spatial disorientation may be facilitated by a description of recent developments which have identified two kinds of visual "systems" with different properties. These two "modes" of vision are recognition and visual guidance. Recognition vision is familiar because it is involved in reading and identifying persons and objects. Its properties are also well known., When illumination is lowered or the quality of the retinal image is impaired by blurring, recognition vision is impaired. Recognition vision is also well represented in consciousness. We are aware when we recognize an object or person. When vision is referred to, it concerns the recognition mode in almost every case. The vast majority of the basic and applied visual literatures describe recognition vision.

The other less well studied aspect of vision is visual guidance which subserves spatial orientation. Spatial orientation is not a simple function of vision alone but rather involves interaction among vision, vestibular, and proprioceptive inputs. In considering the role of vision in spatial orientation/disorientation, it is essential to recognize the interplay of vision with these other senses. In addition to its interaction with the vestibular and proprioceptive systems, orientation vision has a number of characteristics different from recognition vision. If the image is blurred or illumination is lowered, the ability to recognize objects is impaired.

However, under these same conditions, spatial orientation is unaffected. Fig 1 presents the relative efficiency of recognition and visual guidance as a function of illumination. The curve for recognition, which is based on literally hundreds of experiments, represents one of the most fundamental functional relationships of sensory function. As illumination is increased, the ability to see detail, to make stereoscopic depth discriminations, or to recognize objects increases systematically before leveling off at approximately the illumination available in a well lit room. (The discontinuity in the curve occurs at the transition point between rod and cone vision at about the illumination provided by a full moon.) This is one of the most valuable functions in human factors engineering because it allows one to predict accurately human recognition capacities over the entire functional range of the visual system.

The data for the visual guidance curve, which are based on only a small number of studies, suggest that as long as something can be seen, spatial orientation operates at its maximum capacity. In particular, note the trends of the two curves in the area where recognition is degraded by lowered illumination. In spite of the rapid loss of recognition capacity, spatial orientation is unaffected. Only at very low levels of vision near absolute threshold for the rods do we find an impairment in visual guidance. Based on the limited available information, it appears that optical blur has a similar differential effect on recognition and visual guidance.

In addition to the selective degradation of recognition and visual guidance under lowered illumination or optical blurring, the two modes of vision differ with respect to our awareness of them. While recognition is well represented in awareness, visual guidance is typically carried out reflexively or with marginal awareness. A convenient way to illustrate these differences is to consider what happens when we attempt to read and walk at the same time. This is illustrative of a common occurence in aviation and other man-machine situations in which an operator is required to carry out two or more tasks simultaneously. In this case, the dual task is performed readily. One can walk and simultaneously avoid obstacles even though attention is dominated by the material being read. However, if recognition vision is degraded either by reduced illumination or by optical blurring, reading is no longer possible although walking while avoiding obstacles can be carried out without impairment.

The differential impairment of recognition and visual guidance is referred to as the selective degradation of vision and has been implicated in the disproportionate frequency of automobile accidents at night. The reasoning is based on the fact that at night visual guidance or steering the vehicle can be carried out as well as during daylight with the consequence that the driver feels self confident about her/his ability to control the vehicle and is not aware of the degradation of recognition vision. Since steering is a continuous task, the driver receives steady confirmation of the ability to steer and is not prepared for the infrequent demands on her/his degraded recognition abilities. This unjustified self-confidence is exacerbated by alcohol or other drugs which artificially increase self-confidence with our concomitant improvement in sensory or motor abilities.

Our ability to analyze any problem, particularly those involving human-machine interactions, is facilitated by our understanding of the basic mechanisms involved. Recent approaches to the problem of spatial disorientation and motion sickness have identified the correspondence among the visual, vestibular, and proprioceptive inputs as compared with the previous history of the individual. In the vast majority of cases, movement of the head results in simultaneous movement of visual contours in the opposite direction. However, in a closed compartment such as a cockpit or ship in which the terrain is not visible, movement of the head is accompanied by movement of visual contours in the <u>same</u> direction. Under these conditions, the gaze stability mechanisms which are so essential to spatial orientation are receiving incompatible signals. The vestibular signals indicate motion of the eyes in the direction opposite to head motion (vestibular-ocular reflex) while the visual guided optokinetic system signals motion in the same direction. Although spatial disorientation and motion sickness are most probably not a result of any single factor, there is every indication that the <u>mismatch</u> among the sensory systems subserving gaze stability plays a significant role in spatial disorientation and motion sickness not only in aircraft but also in flight simulators. In analyzing this problem, it is helpful to keep in mind that the characteristics of the visual system are related to the visual guidance mode rather than to recognition vision, i.e., independence from illumination, blur, (and probably color) and the predominant influence of large moving contours.

This approach may also provide insight into methods for ameliorating spatial disorientation. Because visual guidance does not require the appreciation of detail, it can be subserved adequately by the periphery of the visual field. This is illustrated by the reading and walking example in which the central visual field is occupied with the reading material while the periphery is mediating visual guidance. It can be also demonstrated by covering the central field with one's fists and attempting to walk. If there are no obstacles to locomotion, visual guidance can be carried out adequately with the peripheral visual fields.

The predominant role of the periphery in visual guidance is one of the bases for the Malcolm Horizon which is designed to aid orientation by stimulating a large area of the peripheral visual field. There are a number of potential advantages of the Malcolm Horizon in addition to the fact that it utilizes the portion of the visual field which normally subserves spatial disorientation. One of the problems encountered in high stress situations is narrowing of the visual field or "functional tunnel vision" which is characterized by a lack of awareness of peripheral stimuli. However, there is some indication that this narrowing does not affect our ability to orient with peripheral stimuli at least when the narrowing results from the "coneing" of attention. It may well be the case that stress selectively degrades recognition vision while not affecting visual guidance. (It is still an open question whether narrowing resulting from physiological factors such as those associated with high G forces or hypoxia will also influence the orientation system.) It is axiomatic in human engineering,, and especially in aviation, that one should strive to reduce demands on the pilot's attention. This not only frees the limited attentive capacities for tasks which demand cognitive interpretation, but also avoids the interference with cognitive tasks during periods of stress and high perceptual-motor load. Any system which provides for spatial orientation while minimizing demands on awareness, as is normally the case, should serve to increase efficiency.

Q: Inaudible

HWL: It might be disconcerting because you'd have double vision, but I'm not sure it would affect motion sickness. The double vision would affect spatial orientation but I'm not sure motion sickness would be a consequence of it.

Dr. William Richardson: Would you comment on the role of focal mode in SDO followed by sudden awareness of the ambient situation.

HWL: One of the requirements of this approach, which is somewhat simplified, is I implied we normally orient with the ambient system and normally that's true. But, we can also orient with the focal system. Suppose for example, you're driving down a road at night and all you can see is a white stripe. If it's a DeLorean car, it sucks up the white stripe. That's a Bob Hope joke I heard last year. The worst part is I didn't understand why is was funny until I asked one of the students. It's possible to follow the white stripe with focal vision, so you can orient with the focal system. You're using the modes rather inefficiently, because the function of the ambient mode is to carry out orientation unconsciously. We don't usually want to think about orientation - that's why when we talk about it in a situation like this we have to describe what it is, because it's usually unconscious. What you're doing is using a different mode entirely. Now whether that leads to motion sickness I don't know. But that's not a usual use of that mode. It was brought out before, that we can do a lot of things and overcome a lot of errors in our mechanical systems by training. That's an example of using a system to perform a job it wasn't optimally designed to do. But, I don't know whether it would lead to motion sickness.

B/G DeHart: Inaudible comment about use of focal vs ambient mode on generating or coping or fighting with situations of disorientation, distraction and loss of situational awareness.

Dr. William Richardson: Barely audible comment: It's as though there's a break in the sequence of information received by the brain as the distraction or disorientation occurs. And when you come back to re-orient, to the new situation, you find it very difficult to re-establish that sequence of attention or pattern in the brain, or whatever you call it, and it takes some time to do it.

HWL: I'm not a pilot but I can imagine this is a problem when you go inside-outside because you're going from one system to the other. Is that what you're saying?

DWR: Yes.

Unidentified: Inaudible - regarding focusing on the symbology of HUD's, outside-in vs inside-out, peripheral cues. Can one ignore the peripheral cues when looking through the HUD - or should one go head-down to get rid of them? Is it better to look at the round dials or the HUD? What's the impact of background of the HUD i.e. flying through featureless cloud, moving cloud, broken cloud, any other precipitation, anything that moves in the HUD FOV that might generate distraction, vection or disorientation? (However, most of this question/comment was barely audible.) Do you see the background through the HUD?

Dr. Richard Haines: We had the opportunity to look at that very issue with simulation using HUD's at NASA-Ames. The Boeing 727 flew manual ILS approaches with ceiling of 250 feet and RVR of category 2. During some of the approaches, we had another 727 (model) sitting on the end of the runway. The question was whether looking through the HUD, they saw the obstruction in time to initiate a go-around. They had 14 seconds and were aware of the possibility of obstruction. Subjects were experienced airline captains. Two of the 8 never saw the 727 because they were really concentrating of the HUD, and they had quite a bit of experience by then. Of the other 6 pilots, 4 had very late responses and we calculated at least a tail strike or a wingtip strike. So, I think the issue is really cognitive switching there. It raises some fundamental questions regarding conspicuity of focal vs ambient trade-off.

Joe Bill Dryden: The book claims that the HUD is focussed at infinity and, indeed, that's not the case. In landing you're looking at the HUD and the rest of the world is not quite in focus, and it takes some practice to get good landings.

General discussion, inaudible, uninterpretable, followed immediately by Ms. Joyce Iavecchia's comments.

FOCUS TRAPPING POTENTIAL OF HUD'S

Ms. Joyce H. Iavecchia

Naval Air Development Center, Warminster, PA

BIOGRAPHY

Ms. Joyce H. Iavecchia, a native of Philadelphia, PA, attended Temple University to obtain a bachelor's degree in Psychology (A.B., 1976). She went on to the University of Illinois at Champaign - Urbana, for graduate study in Engineering Psychology (M.A., 1979). Since 1979, she has been employed by the Naval Air Development Center (NADC), Warminster, PA. Currently, she is cognizant engineer for the design of the A-6F and F/A-18 crewstations. While at NADC, she has conducted research on head-up display problems. She is especially interested in virtual imaging display design improvements and pilot accommodation training.

My sister, Helene, and I and Stan Roscoe have often looked at that problem at NADC, and you have to remember that although the head-up display is focussed at optical infinity we have another system of the human that's involved, and we actually get a measurement of where people are focussed. When you're using a head-up display, you find that it's not at optical infinity. The difference is that they're focussed much closer, nearer their dark focus, which is the distance to which an eye will accommodate when at rest, as in a dark room, where there is no stimulus to tug the focus outward. It's considered to be a resting focal distance for the eye. So what this is telling us is that the display image of a head-up display is not a very powerful stimulus to the eye but it is a very weak stimulus. And where the eye is focussed at in using the head-up display is really much more dependant on the background scene than on the HUD. If a person looks at the distant scene through the HUD combiner with the symbology turned off, he will tend to focus on the scene - closer to optical infinity. But as soon as the symbology is turned on, he will tend to focus inward, closer to his own resting dark focus. His acuity for things beyond then becomes compromised. In other words, despite the fact that the HUD is collimated at infinity, the eye does not necessarily focus at infinity when looking at the HUD. The eye may focus closer, to some intermediate distance, such as the individual's own resting dark focus, or perhaps on the surface of the combining glass. So actually, there's a compromise between looking at some distant target, and the HUD, which is keeping your eye focussed inwards.

Dr. William Richardson: In other words, you have to accommodate continuously if you're using distant targets and the HUD.

Dr. Jerry Gard: We're very careful to insure all the symbols on the HUD are focussed at infinity - (remainder inaudible).

JHI: We measured focus distances through the center of the HUD.

Unknown: Do we know how one switches focus from the HUD to beyond?

Dr. Richard Malcolm: Two comments to two different questions: the first has to do with this business of solving the switching. It would be very surprising if we had the ability to do very much about what's happening to the ambient system because it's a sub-conscious system. So where we have that concern about whether we can effectively moderate the way we perceive data via the ambient system, is a very good one. How can you turn around and moderate what's going on and alter your perceptions that are occurring at a subconscious level when you don't even know how you're doing it? It's a very sophisticated training route that you'd have to become involved in, and I'm not sure we even understand it, how you'd go about training to moderate or somehow alter that ambient system to any great degree.

Dr. Richard Malcolm: The second comment that I'd like to make had to do with the lack of fusion of the image on the two eyes leading to motion-sickness. I should point out that Dr. Tom Dobie in the UK has had a program where he has deconditioned people to motion-sickness, and this has since been replicated by Allan Benson, with a better that 90% cure rate at the 10 year mark of people who go through the deconditioning. To make a long story short, what he seems to think is happening, is that people who are motion sick are actually reacting with the symptoms of nausea and vomiting to a high degree of stress. He enables them to accommodate the stress better by certian kinds of training in bizarre moving environments. Well, it's entirely possible that having double vision is a very stressful thing, depending upon what brings it on, why it occurs, where you find yourself when it occurs, because it sure ruins your ability to concentrate when you suddenly can't bring an image back into fusion. And it's possible that what we're looking at is that people who are apparently motion sick at the same time double vision occurs, what they're doing is reacting to the stress of having double vision at a time when they need good vision. Dobie teaches a coping strategy resulting in a successful transference.

Unidentified: That's very reasonable.

VERTICAL DISPLACEMENT SENSITIVITY ACROSS THE HORIZONTAL VISUAL MERIDIAN FOR VARIOUS STIMULUS RATES, DURATIONS, AND LENGTHS

Richard F. Haines

Aerospace Human Factors Research Division
Ames Research Center, NASA
Moffett Field, CA 94035

BIOGRAPHY

Academic Background:

University of Washington, Seattle, College of Engineering, 1955-57; Pacific Lutheran College, Tacoma, B.A., (Psychology), 1960; Michigan State University, East Lansing, Michigan, Dept. Psychology, M.A. (Experimental Psychology), 1962; Ph.D. (Experimental Psychology/Physiology), 1964; Foothill College, Los Altos, CA; FAA Ground School, 1977.

Past and Present Employment:

Boeing Airplane Co., Renton, WA (Engineering Div.), 1958-9; W.C. Nickum & Sons, Naval Architects, Seattle; Grad. Teaching Assistantship, Michigan State Univ., East Lansing, (Department of Psychology), 1962-3; Predoctoral Research Fellowship, N.I.M.H., M.S.U. (Dept. Psychology) 1963-4; Postdoctoral Resident Research Associateship, N.R.C., at NASA-Ames Research Center, Moffett Field, CA, 1964-7; Research Scientist, NASA-Ames, 1967-present.

Consulting:

Stanford University School of Medicine, Dept. of Preventive Medicine, Effects of CO on visual sensitivity, 1966-1967; TRW-Systems Group, Los Angeles, Effects of light flashes on subsequent visual capabilities, 1969-1970; Expert (legal) witness on eight cases involving surface and aircraft vehicle collisions, pedestrians, etc. (1970-present).

Current Professional Responsibilities:

Dick directs two separate programs of research at Ames Research Center. The objective of the first (1983-present) is to gain a better understanding of which visual cues pilots rely upon to land aircraft under a variety of visual conditions. Such data will be useful in designing future cockpits. The second area (1984-present) is related to developing design guidelines for windows on America's Space Station. Both projects involve active management of teams as well as hardware design and development, carrying out the research, analyzing data, and preparing technical reports of the findings. He also serves on a NASA source evaluation board related to contract support for the Man Vehicle Systems Research Simulator Facility.

Publications:

Author of over 35 scientific journal articles in the following publications: (Aerospace Med.; Human Factors; Amer. J. Optom. and Physiol. Optics; Amer. J. Ophthalmology; Aviation, Space and Environ. Med.; J. Applied POsychol., J. Appkied Physiol., Perception and Psycholphysics; Psychonomic Science; Amer. Inst. of Architecture J.; J. of Navigation; J. of Psychol.; Adv. in the Astronautical Sci.; Man-Environment Systems; Soc. for Information Display; Bulletin of Aerial Phen. Res. Organ.; others). Author/coauthor of many NASA and FAA in-house technical reports; Ed. of UFO Phenomena and the behavioral Scientist, Scarecrow Press, New Jersey, 1979 and author of Observing UFOs, Nelson-Hall, Chicago, 1980. (former) Assoc. Editor of KRONOS-Journal of Interdisciplinary Syntheses.

Personal:

Dick Haines is married and lives in Los Altos, California with his wife Carol and two teenage daughters and is active in a number of local activities. His favorite hobby for some time has been the scientific study of anomalous phenomena with two books currently in preparation on the subject.

ABSTRACT

The vertical displacement threshold (DT) was quantified in 24 observers at each of eight retinal positions along the horizontal meridian (2°, 10°, 30°, 40°, 50°, 60°, 70°, and 80° arc) to the right of the fovea and at the fovea at the start of the horizontal line stimulus' downward movement. Three stimulus durations (from 0.25 to 4 sec) and three angular rates (from 0.04 to 0.42 deg arc/sec) were quantified at these retinal positions to determine whether the displacement threshold is mediated predominantly by an image displacement or rate-sensitive mechanism. Stimulus length was increased incrementally with eccentricity angle from the fovea in accordance with the cortical magnification factor to determine whether the peripheral retina's ability to discriminate small displacements can be improved by increasing stimulus length. The results indicated that: (1) mean percent correct judgments of stimulus displacement decrease with angular separation from the fovea for both the one deg arc long stimulus as well as the progressively longer stimulus. However, when the stimulus is systematically lengthened, accuracy is significantly greater at each retinal location ($p < 0.0001$). (2) stimulus angular rate and duration increases produced significant improvement in displacement accuracy at the 10° and 30° image positions but not at 40° from the fovea and beyond, and (3) mean confidence was significantly influenced by each of the four variables tested depending upon which stimulus image positions was being tested; stimulus

position, and duration were significant for the 40° through 80° image positions as was the stimulus length by rate two way interaction. In general, increasing the magnitude of any of these variables lead to higher mean confidence. These data show that it is possible to partially compensate for the peripheral visual system's reduced capability to discriminate displacement by lengthening the stimulus in accordance with the cortical magnification factor. Because this modification alone does not produce discrimination equivalent to that found at the fovea it suggests that there are other factors which should be taken into account. Stimulus intensity, velocity, and contrast are considered to be the significant factors. These data have potentially important implications in the design of future ultra-wide angle attitude displays for aircraft.

INTRODUCTION

This study was carried out in conjunction with a separate study of the displacement threshold (DT) to stimuli of various lengths, durations, and angular rates imaged along the vertical retinal meridian (Haines, 1984b). A review of prior research dealing with these stimulus parameters was given along with justifications for carrying out both studies. The interested reader should consult the earlier report in regard to these subjects. It is appropriate to provide an abbreviated overview of the rationale for using the cortical magnification factor as the means for determining stimulus length as an independent variable.

Cortical Magnification Factor.

Among the known invariances of visual perception is one having to do with a retinal stimulus image position scaling law derived from neurophysiological research. It is defined as the relationship between the linear extent of primary (striate) visual cortex in millimeters to which one deg of visual angle projects. This scaling law will be referred to as the *cortical magnification factor* (CMF). The quantification of the CMF presented by Virsu and Rovamo (1979) is used here. In applying the cortical magnification factor to measures of peripheral visual acuity, for example, acuity is found to remain invariant with eccentricity when the test pattern's size is increased to correspond to the CMF (Drasdo, 1977; Rolls and Cowey, 1970; Whitteridge and Daniel, 1961a,). The same invariant effect has been found for contrast sensitivity in the periphery (Koenderink et al., 1978). More recent research on spatio-temporal correlation (i.e., movement within a two-dimensional random dot pattern) where eccentricity angle is appropriately varied with certain features of the pattern has suggested that coherent movement in the periphery is also mediated by a particular scaling law of the CMF type (van de Grind et al., 1983). These last authors remark, "It was found that the motion-detection performance is roughly invariant throughout the temporal visual field, ***provided that the stimuli are scaled according to the cortical magnification factor to obtain equivalent cortical sizes and velocities at all eccentricities.*** (italics mine).

As Virsu and Rovamo (1979) have pointed out, use of the cortical magnification factor in designing stimuli to be used in psychophysical studies makes it possible to predict the visibility of various aspects of contrast gratings independently of their size and visual field location. Data from the present study should provide a basis for determining whether the cortical magnification factor applies to the displacement threshold along the horizontal meridian as well.

In summary, four independent variables are of interest here. Stimulus length was varied as a function of the cortical magnification factor with a one degree long stimulus included at each retinal position as a control. The stimulus was imaged at various positions along the horizontal meridian (and at the fovea) to determine how DT varies in the periphery during binocular viewing. Finally, duration and rate of displacement also were varied so as to partially replicate two previous studies (Haines, 1984b, 1984d).

METHOD

Procedure and Test Design. The procedure is the same as described elsewhere (Haines, 1984b). Briefly, each observer read printed test instructions (Appendix A) and then was given a blackboard demonstration of the general nature of the judgment to be made on each sequention, paired-comparison trial. An eye test battery (Ortho-rater, far series) then was administered to ensure that all Os possessed 20:20 or better distance acuity, full and normal binocular field sensitivity, normal horizontal and vertical phoria balance, and normal color perception. Once in the darkened laboratory the O's head and eyes were carefully positioned to lie at the focal point of the stimulus display optical system described below. At lease one practice session consisting of 16 paired-comparison trials was given using similar angular amplitudes and rates as used in the study. Questions were answered during this time concerning the correct toggle switches to use.

Each O remained in the semi-darkness of the laboratory for at least 15 min prior to data collection. The stimulus was then adjusted to an intensity 2 $\log_{10}$ above O's binocular light threshold for the fovea and, separately, for 40 degrees to the right of the fovea.

The test procedure required O to fixate a small (2' diam) point source of dim white light located at the center of the forward visual display throughout testing. He was to attend to each of two trials which were separated by a 0.2 sec blank interval. On each trial in a pair, the stimulus appeared at the center of the display for 1.5 sec after which it descended at a constant angular rate to a new position. The stimulus remained in its final position for 1.5 sec before it disappeared. The response interval followed each pair of trials.

The first response required was a judgement of whether the first or the second trial in a sequential pair descended the farthest. This was done using one of two toggle switches. Following this response O had to indicate how confident he was that his forced choice was correct. A scale from one to nine was used where nine = maximum confidence, five = average confidence, and two = minimal confidence. If the displacement on the two trials appeared to be so close that the response had to be made on the basis of a guess, toggle number one was to be pulled. The observer initiated each pair of trials by pulling a "next trial" toggle.

Stimulus Angular Rate and Duration Variables Studied. Figure 1 presents the stimulus rates and durations presented. The upper-left dashed box encloses the 9 test conditions that were presented at the fovea and at 2° to the right of the fovea. The middle box encloses the 9 conditions presented at the 10° and 30° positions to the right of the fovea. The lower-right box encloses the 9 conditions that were presented at 40° through 80° positions to the right of the fovea. The product of rate and duration is given in each cell. It may be noted that 4 cells were purposely overlapped between the adjacent blocks of cells containing the fovea and 2° positions and the 10° and 30° as well as two cells in common with both the 10°, 30° positions and the 40° through 80° positions. Because of this, direct comparison of the displacement thresholds and mean confidence responses was thereby made possible.

Figure 1

Stimulus Angular Rates and Durations Tested
(Cell Values Represent Total Displacement Amplitude)

Stimulus Angular Rate (deg/sec)	Stimulus Duration (sec.)				
	0.25	0.5	1	2	4
0.04	0.01	0.02	0.04	See Note 1	
0.08	0.02	0.04	0.08	0.16	See Note 2
0.16	0.04	0.08	0.16	0.33	
0.25	0.06	0.13	0.25	0.50	1.0
0.33			0.33	0.66	1.33
0.42		See Note 3	0.42	0.83	1.67

Note:
1. These 9 cell conditions presented at the fovea, and at 2° to the right of the fovea.
2. These 9 cell conditions presented at 10° and 30° to the right of the fovea.
3. These 9 cell conditions presented at 40°, 50°, 60°, 70°, and 80° to the right of the fovea.

Each of the two stimulus lengths was presented under each of the cell conditions shown in Figure 1. This resulted in a total of 9 trial pairs per experimental design times two stimulus lengths times eight stimulus eccentricity positions to the right of the fovea plus the fovea for a total of 153 trial pair judgments per O per experiment. Figure 2 illustrates how each of the three groups of 9 trials was presented as a function of stimulus image position. It was not possible to collect data with the stimulus centered 20° to the right of the fixation spot because of apparatus limitations. All data collection was completed typically within a two hour period with a short break given in the middle. Presentation order of the stimulus length, rate, and duration conditions was randomized within each image position condition. Stimulus image position presentation order also was randomized.

Figure 2

Stimulus Image Position and Length Parameters Tested at Each Retinal Image Position.

Stimulus Image Position (deg)	Stimulus Length (deg min.)								
	1°00' (control)	2°27'	3°55'	10°01'	13°22'	17°00'	20°59'	25°25'	30°21'
0°	1								
2°	1	1							
10°	2		2						
30°	2			2					
40°	3				3				
50°	3					3			
60°	3						3		
70°	3							3	
80°	3								3

Note: The number 1 in a cell indicates that the upper-left group of 9 cells of Figure 1 were presented. The number 2 in a cell indicates that the middle 9 cells of Figure 1 were presented. Number 3 in a cell indicates that the lower-right group of cells were presented.

Apparatus. The apparatus has been described in detail elsewhere (Haines, 1984a; 1984b). Briefly, display coordinates and dynamic equations of motion for the stimulus were programmed on a PDP 11/60 computer which provided the required control to an Evans and Sutherland Picture System II display system. The output of this system was displayed on one of two 21 inch Zytron (model A21R-7C) calligraphic monitors. One was located directly in front of the observer while the other could be positioned at any eccentricity angle desired to the right of the first. The tube face of each monitor was viewed by reflection off identical 25 inch (63.5 cm) focal length spherical mirrors and beam-splitter plane mirrors so as to image the stimulus at apparent optical infinity (0.01 d). The mathematical derivation of the stimulus placed it at a geometrically-equivalent position 50,000 feet from the eyes with the eyes at 50 feet height above an imaginary flat ground plane.

The white stimulus subtended two min arc (0.58 mrad) in thickness and and each of the lengths indicated in Figure 2. It always remained horizontal. The fixation spot was located on the center display's vertical center line. The total vertical angle subtended by each collimating display was 22° arc. Each display was surrounded by a diffuse, approx. 3% reflectance, black painted metal frame which was dimly illuminated by two forty watt tungsten incandescent lamps operated so as to achieve an illuminance of 0.004 ft-c., so that O could just discriminate the presence of a stable frame surrounding the homogeneously dark display field.

A low light level closed circuit TV camera was rigidly mounted to the bottom of the center display unit facing O's face. A deep red-filtered, low-wattage tungsten lamp was used to illuminate O's facial region enough to be clearly visible to the experimenter on a monitor. This permitted continuous monitoring of the eye position and approximate visual fixation stability. Lateral and vertical shifts of the head greater than ± 0.25 inch from the nominal focal point of each optical display was not permitted. The O did not know he was being monitored via the TV camera.

Observers. Twenty four male observers took part. They ranged in age from 16 to 37 (mean = 24.4) yrs. Three were licensed pilots having from 50 to 1,200 (mean = 487) flight hours. Only one had taken part in a previous investigation and was already familiar with the procedures; all observers were given the same set of training trials.

RESULTS

This study has quantified the displacement threshold for three stimulus durations, three rates and two lengths at each of nine retinal positions from the fovea to 80° arc to the right of the fovea on the horizontal meridian during binocular viewing. Since both eyes viewed the fixation point and the boundary between the binocular and monocular visual fields overlap at approximately 60° arc from the fovea, stimuli imaged within about 60° from the fovea stimulated both eyes while stimuli imaged beyond about 60° from the fovea stimulated only the right eye.

The data were analyzed initially following the procedure outlined by Guilford (1954) regarding paired comparison, forced choice data. Briefly, the mean proportion (P) of all trials judged correctly as possessing the largest vertical displacement for a given test condition was determined along with its corresponding normal bivariate (Z) transform. These mean proportion correct data were then used as the dependent measure in analyses of variance (Perlman, 1980). Data used in each analysis of variance consisted of mean responses averaged across groups of from seven to fifteen observers according to which random order group they were in.

Because different stimulus rates and durations were presented at various retinal positions [viz., fovea, and 2°], [10° and 30°], [40°, 50°, 60°, 70°, and 80°] to the right of the fovea, a separate statistical analysis was performed on each of these groups. In all cases (except one) the analysis of variance included four (fixed) main effects: stimulus rate, duration, length, and image position. For the 0° image position only one stimulus length was presented. The results for each effect are discussed in separate sub-sections to follow. Guess responses were deleted from the data.

I. Mean Percent Correct Results for the Foveal and 2° Image Position to the Right of the Fovea (Guesses Deleted).

An analysis of variance (Perlman, 1980) was conducted on the mean proportion correct data with two levels of *image position* (0°, 2°), three *angular rates* (0.042, 0.034, and 0.167 deg/sec), and three *durations* (0.25, 0.5, and 1 sec) considered fixed main effects. The stimulus image position and length variables were "between" and stimulus duration and rate "within" factors in this analysis. Stimulus length could not be tested since both lengths were not studied at both image positions.

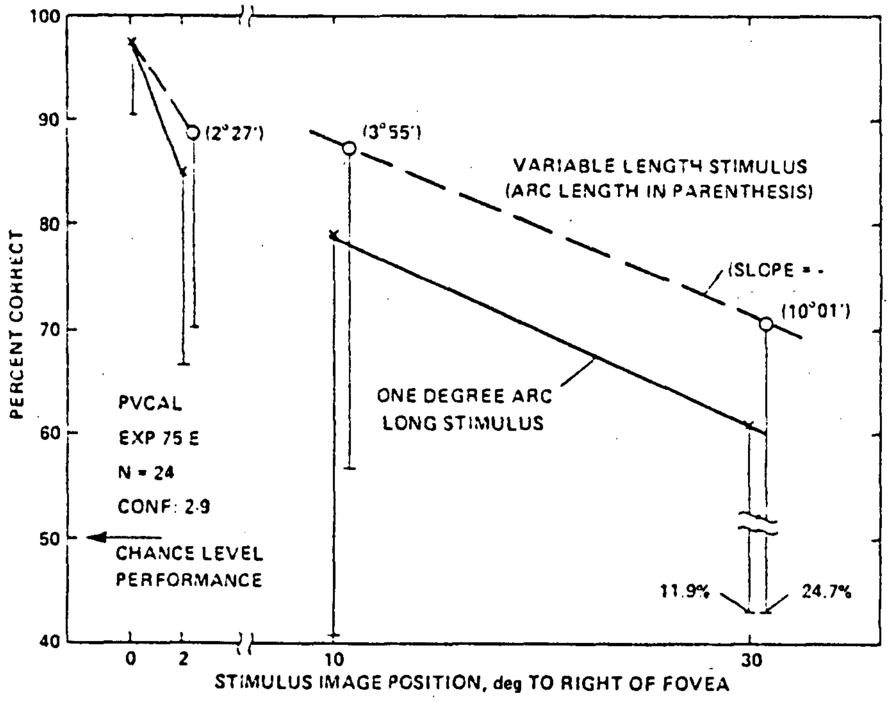
The only significant finding was image position (F = 2248, df = 1/1, p = 0.013). The mean (SD) percent correct was 97.8 (7.2) and 83.8 (22.5) for the fovea and 2° positions, respectively. These results are plotted later (Figure 3) in conjunction with the other data from this study. The rapid fall-off in performance capability within two degrees of the fovea is not unexpected. Similar performance degradation has been noted for a variety of response measures.

II. Mean Percent Correct Results for the 10° and 30° Image Position to the Right of the Fovea (Guesses Deleted).

An analysis of variance (BMDP2V) was conducted on the mean percent correct data for these two image positions. In addition, there were two levels of *stimulus length* (1°, variable at each eccentricity angle), three *angular rates* (0.083°/sec, 0.167°/sec, 0.25°/sec), and three *durations* (0.5, 1, 2 sec). Stimulus image position and length were considered "between" factors while stimulus duration and angular rate were considered "within" factors. As before, guess responses were not included in these analyses. Three of these four main effects were found to be statistically significant. It should be kept in mind that the grand mean data for these two image positions cannot be compared with the grand mean data for the fovea and 2° positions since different values of duration and rate were tested. Nevertheless, these mean results are plotted in Figure 3 together with the results for the 0° and 2° image positions.

Figure 3

Mean Percent Correct Displacement Judgments as a Function of Stimulus Image Positions Between the Fovea and 30° to the Right of the Fovea for Each Stimulus Length.



Stimulus Image Position Results: Mean (SD) percent correct displacement judgments were significantly lower at 30° arc from the fovea than at 10° arc from the fovea (F = 12.03; df = 1/47; p = 0.001). At the 30° position 68.5 (46.5) percent of the judgments were correct compared to 83.3 (37.4) percent correct at the 10° position.

Stimulus Duration Results: Lengthening the duration of the stimulus' movement produced significantly improved performance (F = 3.83; df = 2/94; P = 0.026). At 0.5 sec duration the mean percent correct (SD) displacement judgment was 67.3 (47.1). At 1 sec it was 76 (42.9) percent, and an 2 sec it was 80 (40) percent. This main effect was also found to be significant in an earlier study using similar stimulus parameters but imaging the line stimulus along the vertical retinal meridian (Haines, 1984b).

Stimulus Angular Rate Results: Increasing stimulus angular rate produced a significant increase in the mean percent correct displacement judgments (F = 19.2; df = 2/94; $p < 0.0001$). For the slowest rate of 0.083°/sec mean (SD) percent correct judgment was 58 percent (49.5). For the intermediate rate of 0.167°/sec it was 81.3 (39.1) percent while at the highest rate of 0.25°/sec it was 84 (36.8) percent. Most of the improvement was accounted for by going from the lowest to the intermediate angular rate.

None of the two or three-way interactions or the four-way interaction was significant. It should be noted that the stimulus length main effect was not significant. This was also the case for the 2° and 10° image positions on the *vertical* meridian in the previous study (Haines, 1984b).

III. Mean Percent Correct Results for the 40° Through 80° Image Positions to the Right of the Fovea (Guesses Deleted).

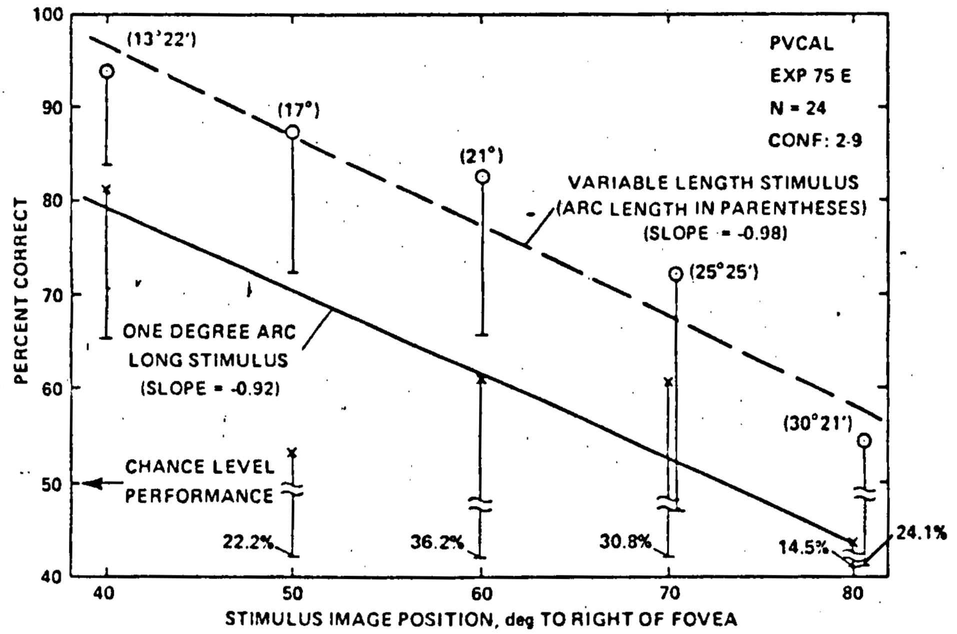
The analysis of variance that was conducted on these mean data (Perlman, 1980) included five levels of *image position* (40°, 50°, 60°, 70°, 80°), two levels of *stimulus length* (1°, variable at each eccentricity angle), three *angular rates* (0.25°/sec, 0.333°/sec, 0.417°/sec), and three *durations* (1, 2, 4 sec). The stimulus image position and length variables were treated as "between" and stimulus duration and rate as "within" factors here.

Stimulus Image Position Results: The analysis of variance showed that as the stimulus was imaged progressively farther from the fovea mean percent correct displacement judgments decreased significantly ($F = 32.6$; df = 4/8; $p < 0.0001$). These mean percentages (SD) were: [40°; 87.5 (15.7); 50°; 70.8 (30); 60°; 71.6 (24.1); 70°; 66.1 (28.2); 80°; 49.2 (30).

The mean percent correct results are plotted in Figure 4 with minus one SD shown for each stimulus image position and length condition tested.

Figure 4

Mean Percent Correct Displacement Judgments as a Function of Stimulus Image Positions Between 40° and 80° to the Right of the Fovea for Each Stimulus Length Condition.

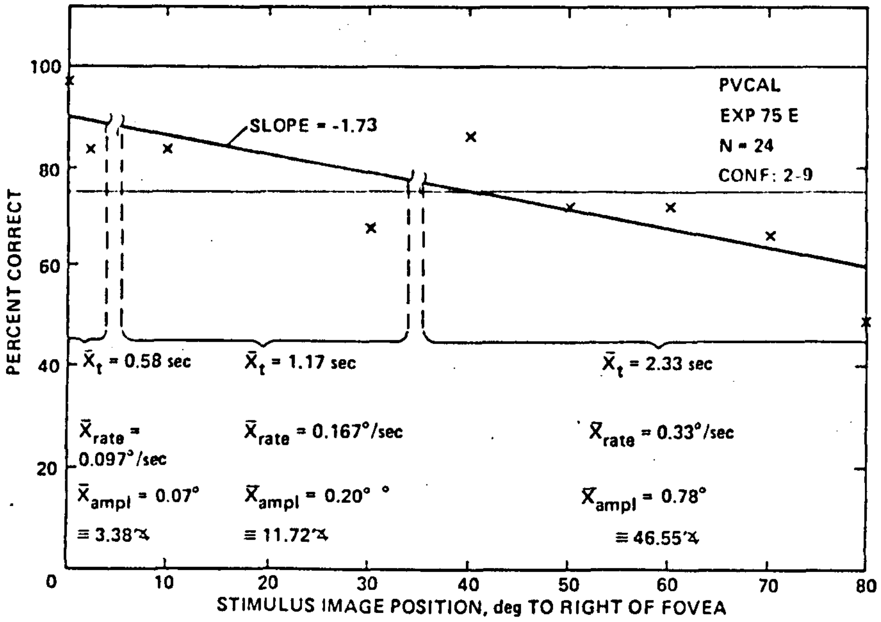


Stimulus Length Results: The analysis of variance showed that the accuracy of displacement judgments was significantly influenced by stimulus length (F = 203; df = 1/2; p = 0.003) such that the mean (SD) percent correct for the 1° arc long stimulus across these image positions was 60.1 (29.4) while it increased to 77.9 (25.2) for the variable stimulus length condition. This same effect was also found for the 20°, 30°, and 40° image positions above the fovea in the earlier study (Haines, 1984b). None of the other main effects or interactions was significant.

Summary of Stimulus Image Position Results Across all Positions: Figure 5 presents mean percent correct across all nine retinal image positions studied averaged across stimulus length, rate, and duration. Since different durations and rates were used across these positions, the use of a single linear, least squares fit curve is somewhat misleading. Nevertheless, the general descending trend in percent correct with increasing eccentricity is apparent. Mean stimulus duration and angular rate for the three separate data groups is given along with the mean displacement amplitude (min arc). It will be noted that the mean displacement amplitude of 3.37' arc for the foveal and 2° positions is 28.8 percent of the mean displacement amplitude of 11.7' arc for the 10° and 30° positions. Likewise, this last value is 25.2 percent of the mean displacement amplitude of 46.55' arc for the 40° through 80° positions. Thus, each succeeding data set to the right in Figure 5 represents approximately a 3.5 times larger stimulus mean displacement than the group to its left which would be expected to elevate mean percent correct in each succeeding group somewhat. This figure does not illustrate the stimulus length effect which is shown in Figure 5 for the 40° through 80° positions.

Figure 5

Mean Percent Correct Displacement Judgments, as a Function of Stimulus Image position Across all Stimulus Image Positions, Rates and Durations and Both Lengths.



IV. Mean Percent Correct as a Function of Angular Rate.

One Degree Stimulus Results: Figures 6 through 10 present mean percent correct plotted as a function of angular rate to illustrate how rate and eccentricity interact. The stimulus length is one degree arc for all figures in this series. Each figure presents the mean data for a separate stimulus duration.

Figure 6

Mean Percent Correct as a Function of Angular Rate for the Fovea and 2° Image Positions for 0.25 Second Duration, One Degree Stimulus Condition.

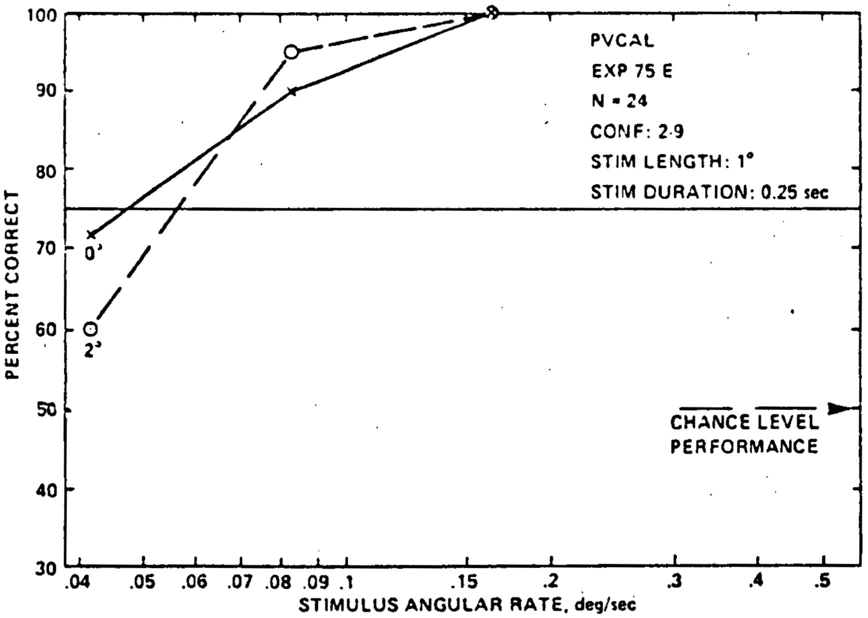


Figure 7

Mean Percent Correct as a Function of Angular Rate for 0° through 30° Image Positions for the 0.5 Second Duration, One Degree Stimulus Condition.

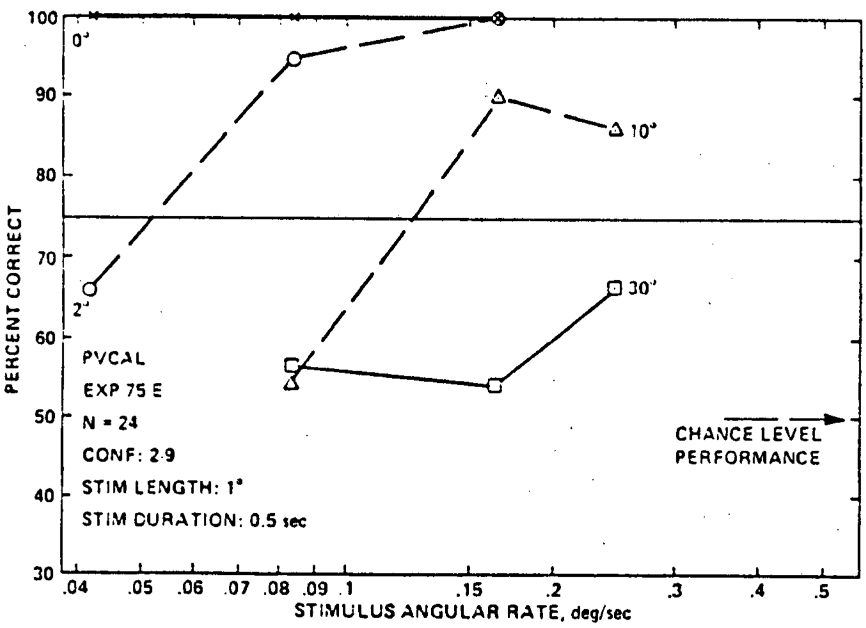


Figure 8

Mean Percent Correct as a Function of Angular Rate for all Nine Image Positions for the One Second Duration, One Degree Stimulus Condition.

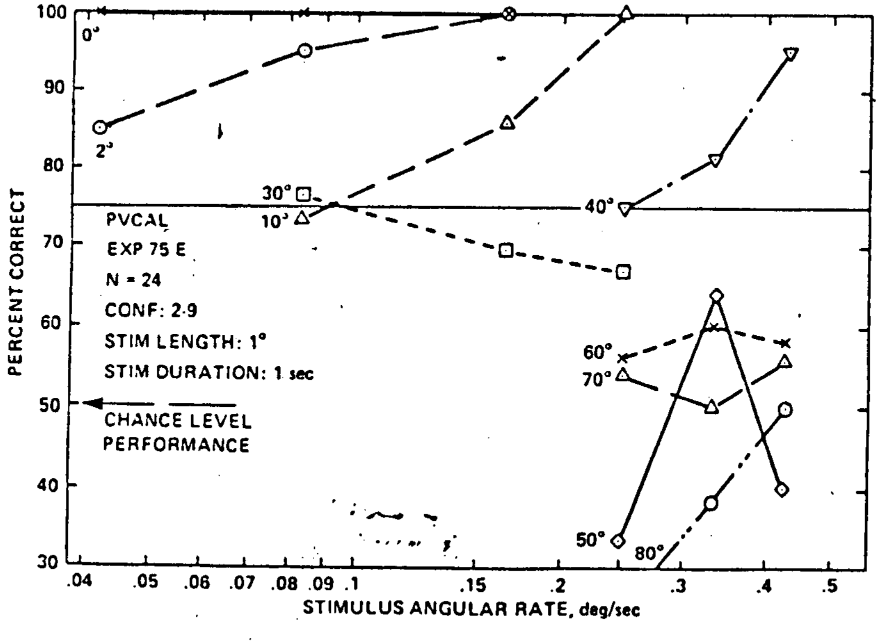


Figure 9

Mean Percent Correct as a Function of Angular Rate for the 10° Through 80° Image Positions for the Two Second Duration, One Degree Stimulus Condition.

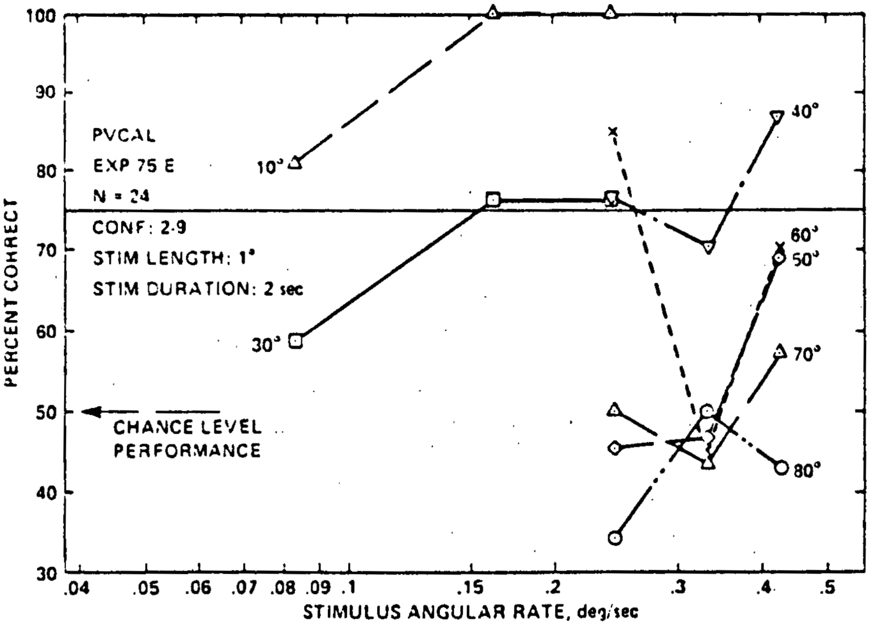
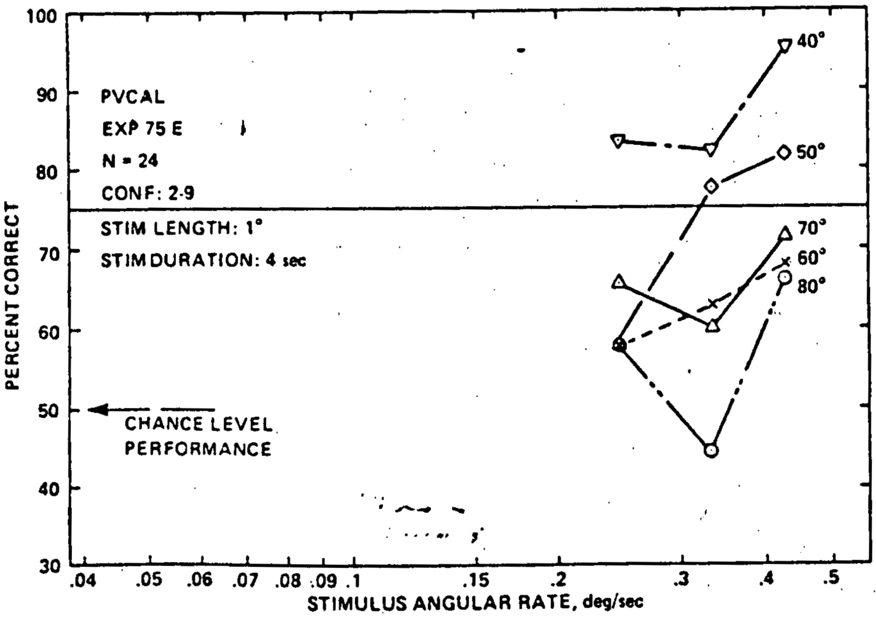


Figure 10

Mean Percent Correct as a Function of Angular Rate for the 40° Through 80° Image Positions for the Four Second Duration, One Degree Stimulus Condition.



Figures 8 through 10 deserve further comment. Comparing the results within any given figure, there is a trend for mean percent correct to decrease with retinal image eccentricity as has been noted previously. Regarding increasingly long durations, it can be pointed out that at the fovea, little improvement is obtained beyond 0.5 sec while at 2° from the fovea, improvement is seen going from 0.5 to 1 sec duration. That is, there appears to be a position-duration tradeoff at this image position. At 10° eccentricity the influence of longer durations is not as clear cut with the greatest improvement seen going from 0.5 to 1 second. At 30° eccentricity and beyond there does not appear to be any clear cut trend in the mean percent correct as a function of duration.

Considering the 40° and larger image positions of Figures 8 through 10, it is important to point out the fairly high accuracies achieved at relatively large eccentricity angles when duration is increased. Thus, above (75 percent) threshold performance was achieved with the one deg arc long stimulus imaged 40° arc from the fovea for all three angular rates tested (cf. Figure 8). The majority of data points in Figure 10 (4 sec duration) are higher than in Figure 9 (2 sec duration). Nevertheless, performance seems to be at or near chance level for stimuli imaged at or beyond 50° arc from the fovea for durations of from 1 to 2 seconds.

Variable Length Stimulus Results: Figures 11 through 15 present mean percent correct as a function of angular rate for the various stimulus durations and variable length stimulus conditions tested. This is to show how image position interacts with angular rate and to provide a comparison with the one degree arc long stimulus data of Figures 6 through 10. In general, the same general observations may be made for the variable length data as were made for the one degree stimulus data: (1) There is a general trend for mean percent correct to increase with an increase in angular rate and for the mean percent correct to decrease with an increase in eccentricity of the image from the fovea. (2) For the shortest duration tested, stimulus length did not have an obvious effect on displacement accuracy within 2° from the fovea. However, for the 2 and 4 second durations the periphery beyond about 40° from the fovea yielded consistently higher accuracy when the variable length stimulus was used. It appears from these data that the far periphery integrates stimulus displacement over longer motion durations than does the retinal locations located nearer the fovea.

Figure 11

Mean Percent Correct as a Function of Angular Rate for the Fovea and 2° Image Positions for the 0.25 Second Duration, Variable Stimulus Length Condition.

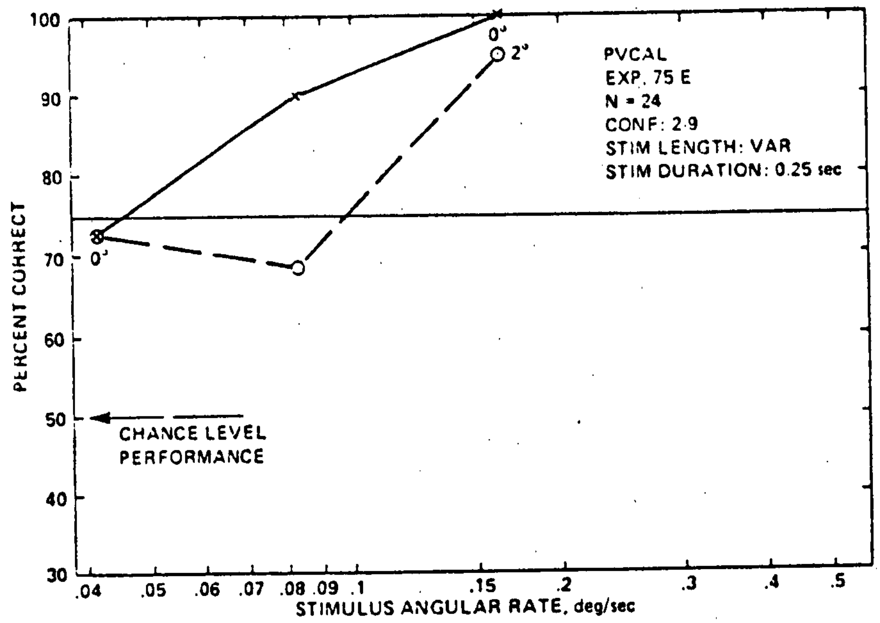


Figure 12

Mean Percent Correct as a Function of Angular Rate for the 0° Through 30° Image Positions for the 0.5 Second Duration, Variable Stimulus Length Condition.

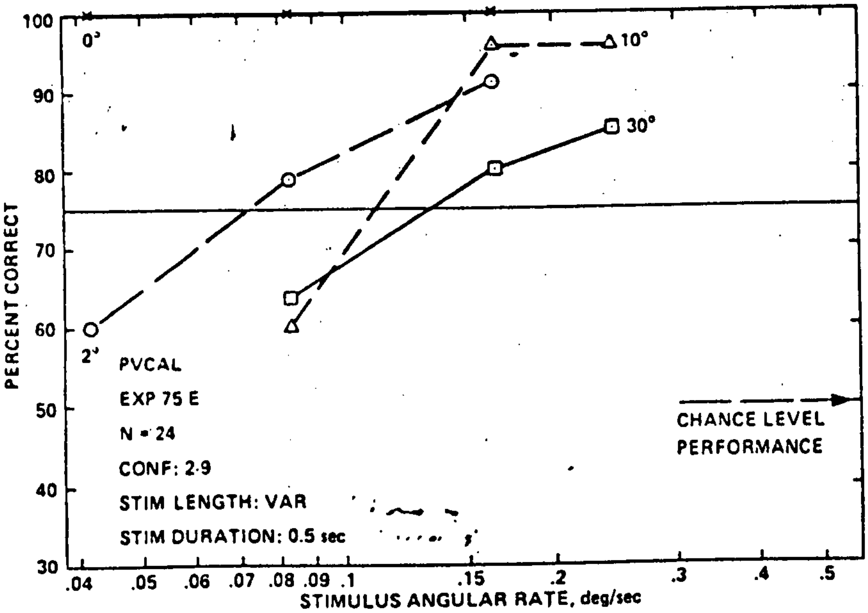


Figure 13

Mean Percent Correct as a Function of Angular Rate for the 0° Through 80° Image Positions for the One Second Duration, Variable Stimulus Length Condition.

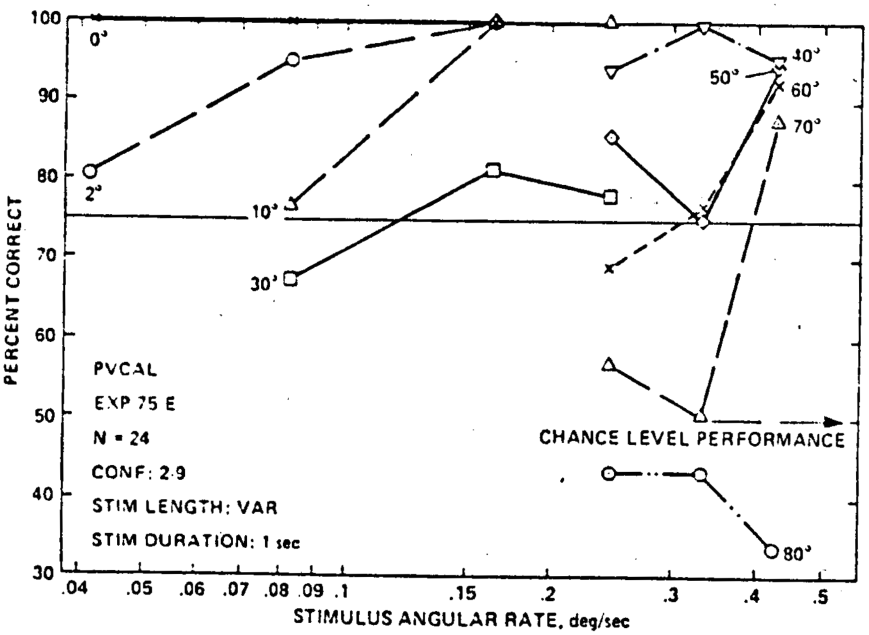


Figure 14

Mean Percent Correct as a Function of Angular Rate for the 10° Through 80° Image Positions for the Two Second Duration, Variable Stimulus Length Condition.

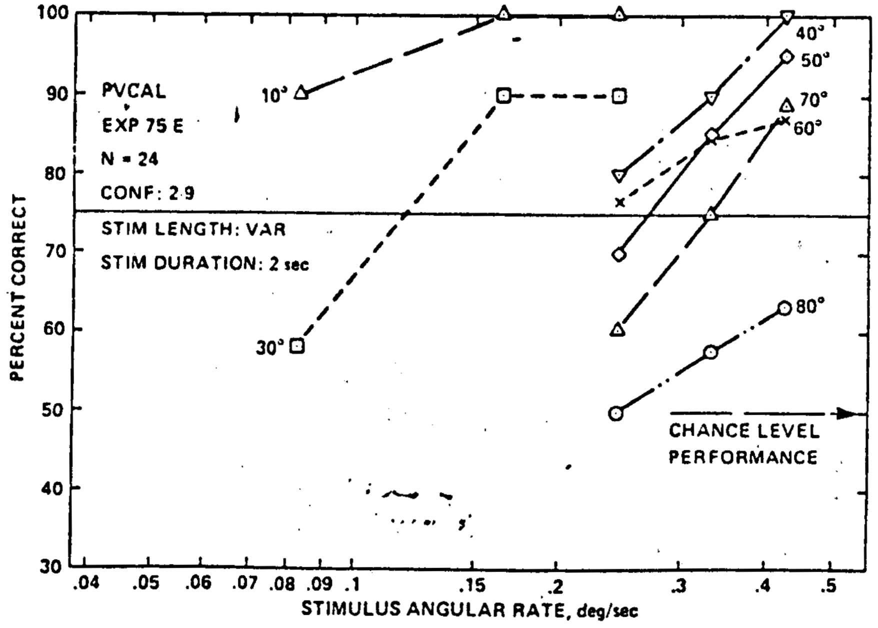
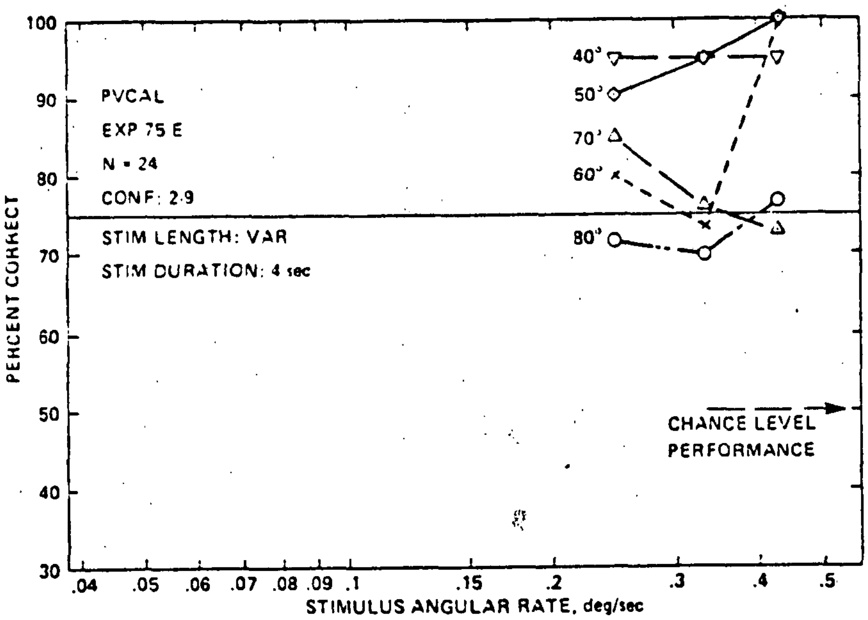


Figure 15

Mean Percent Correct as a Function of Angular Rate for the 40° Through 80° Image Positions for the Four Second Duration, Variable Stimulus Length Condition.



V. Mean Confidence Results for the Foveal and 2° Image Position. (Guesses Deleted).

It will be recalled that only one stimulus length (viz., 1°) was presented at the fovea. Consequently, the stimulus length factor could not be tested here. The analysis of variance (Perlman, 1980) included the same three main effects discussed above in Section *I* and will not be repeated here. The only statistically significant finding was stimulus rate (F = 34.4; df = 2/2; p = 0.028). Thus, mean (SD) confidence at a rate of 0.042°/sec was 5.64 (1.5); at a rate of 0.083°/sec mean confidence was 6.79 (1.2); and at a rate of 0.167°/sec mean confidence was 8.02 (0.9).

A separate analysis of variance was conducted only on the 2° image position mean confidence data since both stimulus lengths were presented. Stimulus duration and rate also were tested as main effects. This analysis showed that both stimulus duration and rate were significant while length was not. An F value of 22.3 was found for stimulus duration (p = 0.007); an F value of 40.4 was found for the stimulus rate main effect (p = 0.002). None of the other main effects or their interactions was significant.

VI. Mean Confidence Results for the 10° and 30° Image Position. (Guesses Deleted).

The analysis of variance (BMDP2V) conducted on these mean confidence data included both image positions and stimulus lengths (both between factors) as well as three *angular rates* (0.083°/sec, 0.167°/sec, 0.25°/sec), and three *durations* (0.5, 1, 2 sec). As before, rate and duration were within factors in this analysis. The findings are presented in separate sections.

Stimulus Image Position Results: Mean confidence was significantly lower at the 30° image position than at the 10° position ($F = 18.2$; df = 1/46; $p < 0.0001$). Mean (SD) confidence = 5.63 (2.52) at 30° and only 3.68 (2.22) at 10°. The image position by stimulus length two way interaction also was significant ($F = 4.78$; df = 1/46; $p = 0.03$).

Stimulus Duration Results: Mean confidence was significantly higher as duration of stimulus displacement increased ($F = 18.1$; df = 2/92; $p < 0.00001$). Mean confidence for 0.5, 1, and 2 sec durations was 4.02, 4.92, and 5.43, respectively. None of the duration interactions was significant.

Stimulus Angular Rate Results: Increasing angular rate produced a significant increase in mean confidence ($F = 24$; df = 2/92; $p < 0.001$). For the lowest rate of 0.083°/sec mean confidence was 3.45; the intermediate rate of 0.167°/sec mean confidence was 5.23, and for the highest angular rate of 0.25°/sec, it was 5.69. The rate by duration interaction was found to be significant ($F = 3.90$; df = 2/92; $p = 0.024$) as was the rate by duration by stimulus length three-way interaction ($F = 3.46$; df = 2/92; $p = 0.036$).

It may be noted once again that stimulus length was found *not* to be a statistically significant main effect in this analysis.

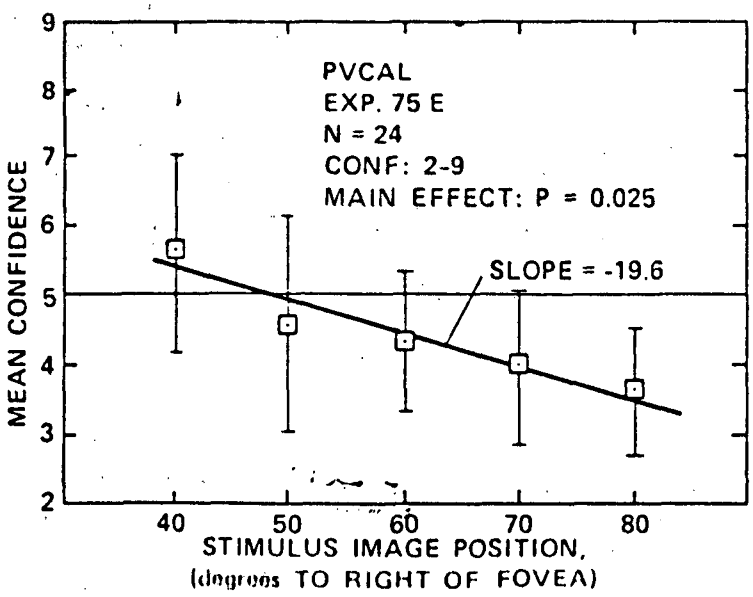
VII. Mean Confidence Results for the 40° Through 80° Image Position. (Guesses Deleted).

The analysis of variance (Perlman, 1980) conducted on these mean confidence data included all four main effects cited in Section *III* above.

Stimulus Image Position Results: Imaging the stimulus increasing far from the fovea produces significantly reduced confidence ($F = 5.08$; df = 4/8; $p = 0.025$) as might be expected. This is plotted in Figure 16.

Figure 16

Mean (± 1 SD) Confidence as a Function of Stimulus Image Position.

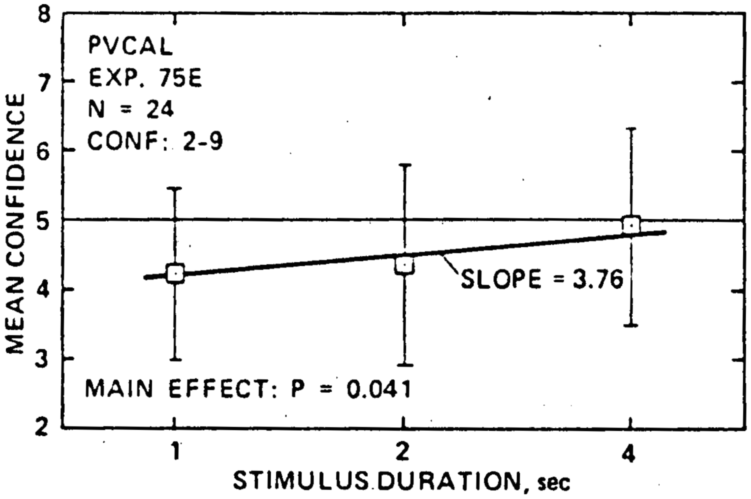


Stimulus Length Results: This factor was not statistically significant. Nevertheless, the longer stimuli tended to yield higher mean confidence, as might be expected.

Stimulus Duration Results: Lengthening the duration of the stimulus' motion produced significanty increased confidence (F = 7.9; df = 2/4; p = 0.041) which is presented in Figure 17.

Figure 17

Mean (± 1 SD) Confidence as a Function of Duration.

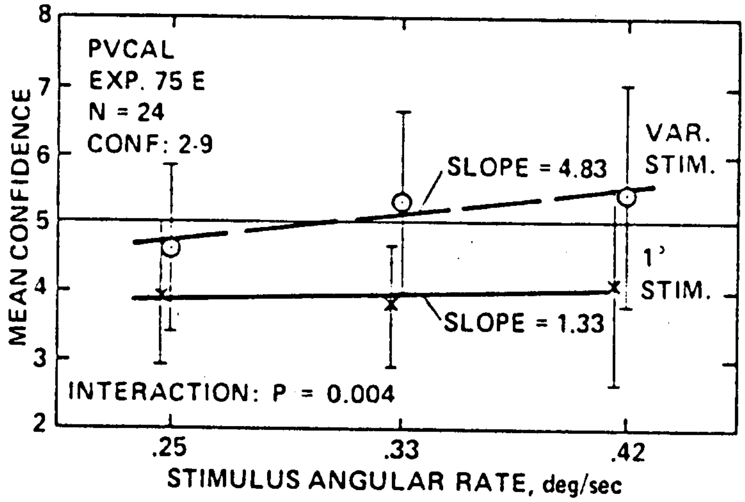


Stimulus Angular Rate Results: This main effect was not significant.

Interaction Results: The analysis found that stimulus rate interacted significantly with stimulus length (F = 29.3; df = 2/4; p = 0.004). Figure 18 illustrates the nature of this interaction which appears to result from a difference in slopes of the two linear, least square curves fit to each data set. None of the other interactions was significant.

Figure 18

Mean (± 1 SD) Confidence as a Function of Angular Rate for each Stimulus Length.



VIII. Mean Displacement Threshold Results.

Two separate analyses of the mean displacement threshold (DT) were made (a) Mean DT as a function of stimulus duration, and (b) Mean DT as a function of stimulus image position.

Stimulus Duration Results: Mean vertical displacement thresholds (DT) across stimulus duration for all stimulus positions were determined using a 75 percent correct criterion. These results are presented in Figure 19 for the one degree stimulus length and in Figure 20 for the variable stimulus length. Figure 19 is based upon interpolations from Figures 6 through 10 where the mean curves passed through the 75 percent correct level. When they did not no data point could be derived for inclusion in Figure 19. Likewise, Figure 20 is based upon interpolations of Figures 11 through 15. On a log-log plot such as this a horizontal line would indicate that the stimulus must move through a constant angular displacement in order to evoke a threshold response while a linear slope of plus one would indicate that velocity and duration are reciprocally related such that DT is determined by a constant angular velocity. It can be noted that for any given retinal image position, the slope of the best fit linear curve tends to increase with increasing retinal eccentricity for both the one degree arc long stimulus as well as for the variable stimulus length. This suggests that the farther into the periphery the stimulus is imaged the more stimulus angular velocity contributes to the judgement. It also may be noted that at each retinal position, lengthening stimulus duration produces an increase in mean DT regardless of stimulus length.

Figure 19

Mean Displacement Threshold as a Function of Stimulus Duration for all Stimulus Image Positions for the One Degree Arc Long Stimulus.

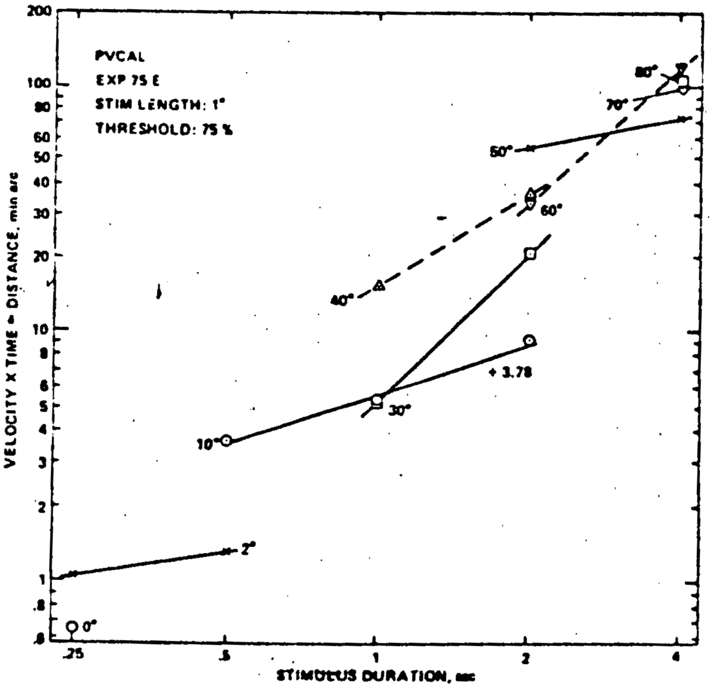
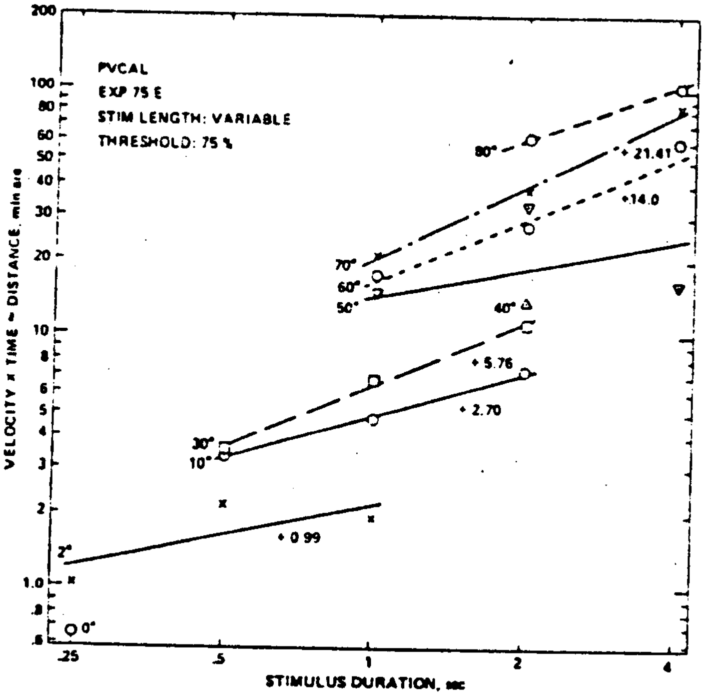


Figure 20

Mean Displacement Threshold as a Function of Stimulus Duration for all Stimulus Image Positions for the Variable Length Stimulus.



Stimulus Image Position Results: Mean DT was also determined as a function of stimulus image position for each duration and stimulus length. These results are presented in Figure 21 for the one degree arc long stimulus and in Figure 22 for the variable length stimulus condition.

Figure 21

Mean Displacement Threshold as a Function of Stimulus Image Position for Each Duration for the One Degree Stimulus Length Condition.

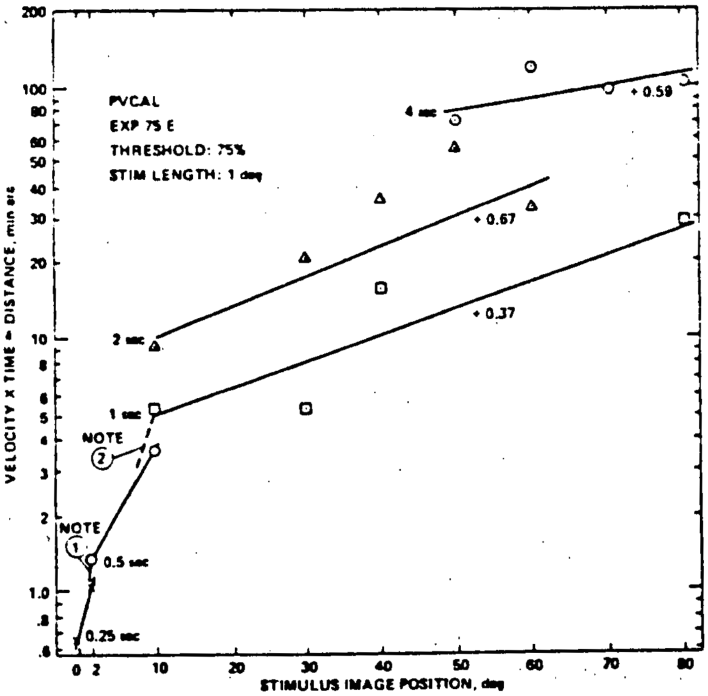
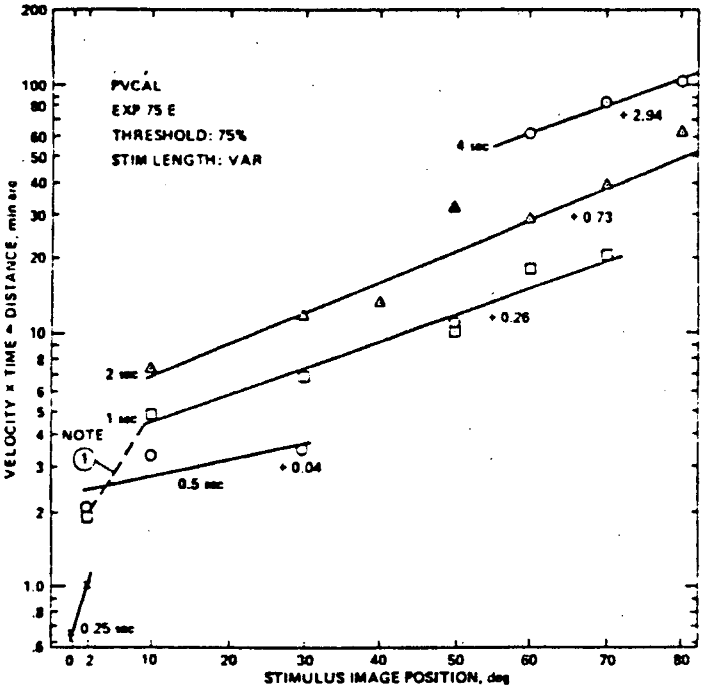


Figure 22

Mean Displacement Threshold as a Function of Stimulus Image Position for Each Duration for the Variable Stimulus Length Condition.



Referring to Figures 21 and 22 it can be noted that mean DT increases with increasing image position eccentricity at all of the durations tested. This finding is implied in Figures 6 through 15 as well. In addition, mean DT tends to be lower (increased sensitive) for the variable length stimulus condition. That is, the longer the stimulus at any given retinal position the less it has to move in order to be correctly perceived as having moved. This has been noted previously by Mattson (1976) and McColgin (1960).

The question may be raised whether or not there is any advantage to be gained by progressively lengthening peripheral stimuli? Referring to Figures 21 and 22 it may be noted that beyond 10° from the fovea consistently smaller mean DTs are obtained for the variable (longer) length stimulus at 1 and 2 sec duration. At 10° to the right of the fovea and two second duration, for example, mean DT decreases from 10 min arc to 6.8 min arc. And at 60° to the right of the fovea and two second duration, mean DT decreases from 40 min arc to 28.5 min arc.

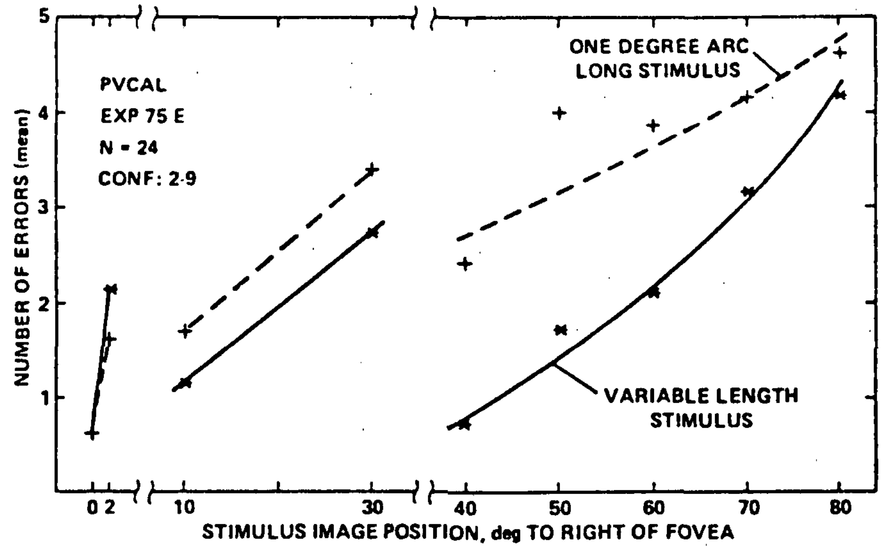
IX. Error and Guess Rate Results.

These data are presented in three sections (a) total errors, (b) total errors committed when O also had a finite confidence that he was correct, and (c) total guesses.

Total Errors. The total number of errors (incorrect choice of which trial possessed the stimulus displacement) were determined for each observer and image position for the variable length stimulus and the one degree arc long stimulus length. They are presented in Appendix B and C, respectively. Figure 23 presents the total errors (mean) as a function of stimulus image position for each of the two stimulus lengths studied.

Figure 23

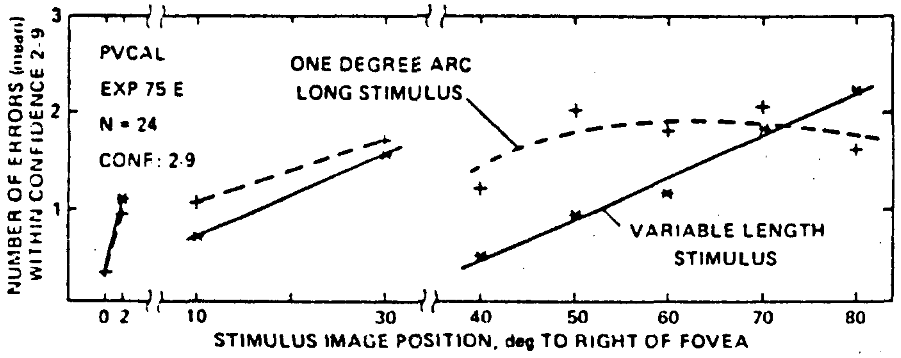
Total Errors (Mean) as a Function of Stimulus Image Position for Each Stimulus Length Condition.



It should be noted that the data for the fovea was simply repeated from the one deg stimulus length for the variable stimulus length in Appendix B and C. The mean (SD) for each image position also is given. It was found that: (a) while the number of errors tends to increase with increasing eccentricity of the stimulus' image the effect is by no means regular. Indeed, there appears to be a rather marked discontinuity at 40° eccentricity, which can perhaps be attributed to the increase in both rate and duration when going from 30° to 40° eccentricity; (b) these errors are distributed over all 24 Os fairly regularly with no single O accounting for a disproportionately large number of errors.

Total Errors Committed When O Had Some Degree of Confidence That He Was Correct. These mean results are presented in Figure 24 and Appendices D and E for the variable and one degree arc long stimulus length condition, respectively.

Figure 24
Total Errors (Mean) Within a Confidence Range of 2 - 9
(i.e., all guesses deleted).

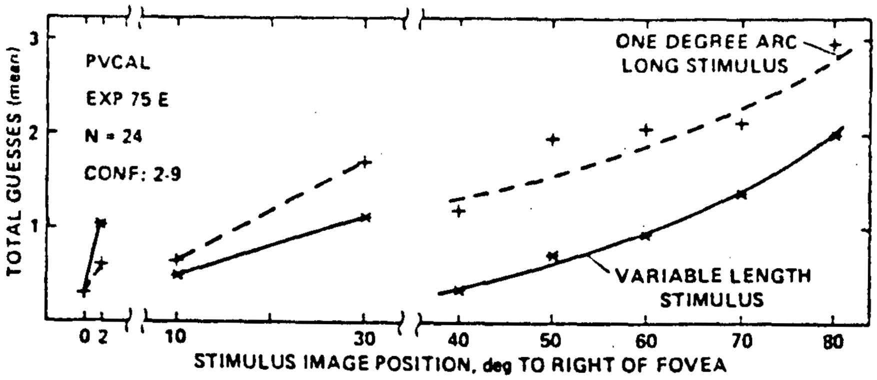


It may be noted that the same general observations as given above for the total number of errors may be made here. It was surprising that these Os had as many wrong judgments as they did while, at the same time, being relatively confident that they were right. The perception of displacement in the peripheral visual field was difficult at best. Often O had only a vague awarness that the stimulus line had "shifted". In some cases O was not even sure what direction it had moved. Also, no single O accounted for a disproportionately large percentage of these "errors made with confidence".

Total Guesses. The total number of guesses made by each O for each stimulus image position is given in Figure 25 and in Appendix F for the variable stimulus length condition and in Appendix G for the one degree arc long stimulus length condition. Inspection of these data show that: (a) there is a general tendency for guess rate to increase with an increased stimulus image angular separation from the fovea, (b) at any retinal image position (except 2° and 40°), fewer guesses were made when the longer stimulus length was presented, and (c) no single O accounted for a disproportionately large number of guesses.

Figure 25

Total Guesses (Mean) as a Function of Stimulus Image Position for Each Stimulus Length Condition.



DISCUSSION

In this study it has been shown that the displacement threshold (DT) increases with an increased angular separation of the stimulus image from the fovea. That is, the stimulus must move farther in order to be correctly discriminated as having moved. Mean DT also increases, at any retinal image position, with an increase in stimulus duration. In addition, within the range of present stimulus parameters, improved displacement sensitivity can be expected by increasing stimulus length, duration, and/or angular rate, a finding in agreement with earlier research from the authors' laboratory (Haines, 1984b, 1984c, 1984d) and elsewhere (Johnson and Leibowitz, 1976; Johnson and Scobey, 1982; Mattson, 1976). While each of these stimulus characteristics may have relevance to a number of different research areas only three topics will be discussed here: (1) the mechanism that may underly this displacement judgment, (2) possible contributors to a composite invariance expression, and (3) one possible application for these results.

Perceptual Discrimination Mechanism. It has been pointed out by Henderson (1971) that the perception of movement should be limited by the capacity of the retina to summate effects over both time and (retinal) distance so that "...the greater the proximity of two stimulations in either of these dimensions, the greater the neural cooperation between their effects and the less (will be) their distinctiveness." Thus, any reciprocity found between DT and stimulus duration implies that such discriminability requires longer delays at shorter separation distances and permits shorter delays at greater distances.

Referring to Figures 19 and 20, it is seen that there is a tendency for the slopes of the least squares fit curves to increase with an increase in stimulus duration at each retinal image location. As has been discussed in details elsewhere, on a log-log plot such as this the steeper the slope the more stimulus' angular velocity contributes to this judgment (cf. Haines, 1984c; Johnson and Leibowitz, 1976 for further discussion).

Some comment is called for regarding the use of different length stimuli imaged at different retina positions and the fact that binocular vision was employed. The typical boundary separating monocular from binocular vision on the right side of the visual field on the horizontal meridian is at (approximately) 60° from the fovea. Thus, a stimulus that extends from less than to greater than this eccentricity will stimulate both modes of vision. Such a circumstance complicates data interpretation at best. Now let us consider the above fact in light of the present stimulus length variable studied.

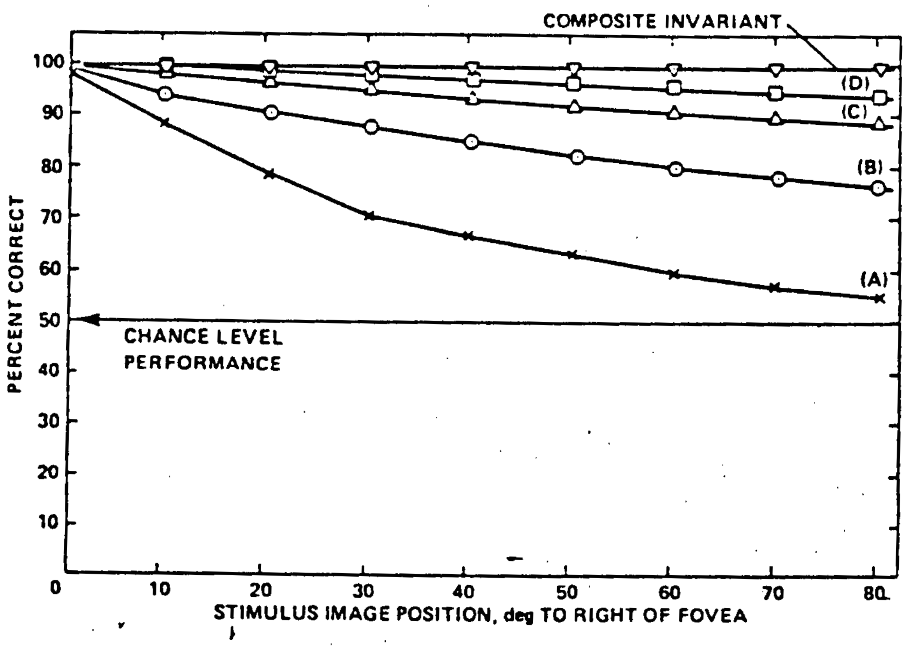
When a one degree arc long stimulus is imaged at some peripheral location at the start of its downward displacement its image will remain upon a relatively limited population of receptors for all of the displacements studied here. Use of a longer (variable length) stimulus at the same peripheral location will necessarily cause the image to be swept across a wider array of receptors. For binocular vision the number of receptors is approximately double that of monocular vision.

Possible Contributors to a Composite Invariant Expression. The concept of the cortical magnification factor acting as a visual field *spatial* invariant was discussed in the introduction to this paper and elsewhere (Haines, 1984b). The fact that stimulus *length* may be increased at increasingly eccentric retinal positions to improve displacement sensitivity was not unexpected since the same effect was found in a previous study of the vertical meridian using closely similar stimulus parameters. Presumably, this particular result is due to the fact that the retinal image of ever-longer stimuli sweep over increasingly large numbers of receptors during its displacement which provide for a higher spatio-temporal correlation. Presumamabably, the higher the correlation the more information is available for "interpretive" cortical centers (Graham et al., 1948; Mattson, 1976). However, since performance is *not* maintained at a fully foveal-equivalent level suggests that the spatial attribute of stimulus length is not the only attribute that must be appropriately varied. It is likely that stimulus intensity also must be increased with greater angular eccentricity to compensate for the progressive fall-off in pupillary aperture viewed at more oblique angles. The author has found support for this contention using a reaction time measure (Haines, 1975). Other stimulus attributes also likely play a part.

If the degree to which perceptual performance in the visual periphery differs from performance at the fovea may be accounted for by an appropriate combination of all relevant stimulus attributes that can be shown to vary with angular eccentricity from the line of sight, then it should be (theoretically) possible to derive a *composite invariant* (CI) expression which one could use to design significantly more "effective" stimuli for placement literally anywhere within O's FOV. This concept is illustrated schematically in Figure 26 where percent correct on the ordinate is plotted as a function of stimulus image position across the horizontal retinal meridian on the right side. The horizontal line at 100 percent is the desired theoretically perfect CI curve for a particular design situation. In most instances this is equivalent to foveal sensitivity. The lowest curve (A) represents the accuracy of displacement judgments derived from the present study where a spatial invariance component related to stimulus *length* has been employed. Curve (B) represents the theoretical performance curve that might result from including a stimulus *intensity* invariant (cf. Haines, 1975) to the stimulus length invariant which produced curve (A). The difference between curve (B) and (C) represents the influence of including a third invariant component to account for regional variation in stimulus *velocity* (cf. van de Grind et al, 1983). Curve (D) represents the theoretical performance curve which might result from including an invariant compoent to account for regional variations in *image contrast* (cf. Koenderink et al., 1978). Of course there may be other invariants as well whose combined influence will result in the uppermost curve labelled as the CI curve.

Figure 26

Hypothetical Distribution of Invariant Components Contributing
to Foveal-Equivalent Displacement Sensitivity
Across Half of the Visual Field.



Of course, an important question is the relative weighting to be given to each invariant parameter as well as whether they are additive, subtractive, multiplicative, divisive or involve some other relationship. No parametric tests have been conducted to date in which all invariants are compared with each other under identical test conditions or using common threshold judgment criteria. This is a task that should receive the immediate attention of investigators. It is suggested that the relative ranking in importance of these stimulus parameters should be based upon established knowledge of which characteristics most influence motion sensitivity. Thus, stimulus angular subtense, intensity, angular rate, and duration likely contribute the most to the CI.

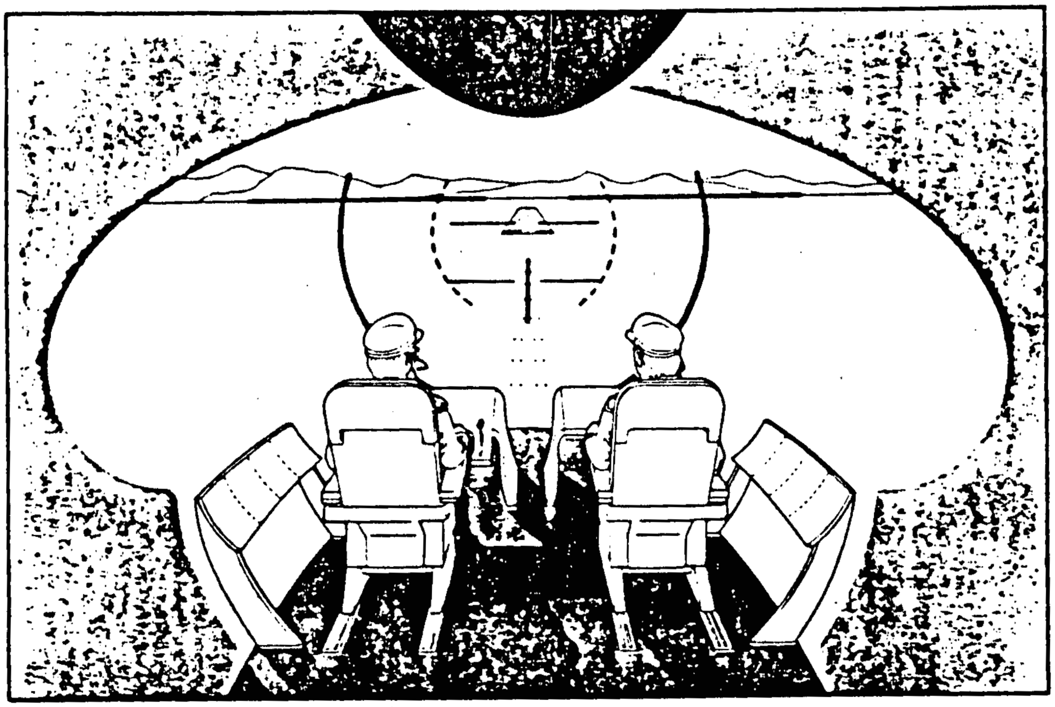
A Possible Application for These Results. It remains to discuss one way which the present mean DT data for the horizontal meridian and previous DT data for the upper half of the vertical meridian (Haines, 1984b) might be applied in an airplane cockpit display symbology design situation. Traditionally, all symbolic (alphanumeric and non-alphanumeric) flight guidance and control information has been provided on separate dials, guages, and other indicators mounted in opaque instrument panels located throughout the cockpit. Due to the need to display a large amount of information, each individual display needed to be relatively small in order to accommodate them all. As the number of different displays increased per unit area of the pilot's field of view another trend also was developing, viz., presenting more than one parameter within a given display (so called multi-function displays). This contributed to increased pilot workload and somewhat lengthened (visual) dwell times on these displays. A subsequent approach to try to help overcome some of these problems was to present certain information on peripherally located displays. A variation of this approach is known as the "Malcolm Horizon" or the "Peripheral Vision Horizon Display" (PVHD) (Anon, 1984).

The PVHD is a cockpit projective display designed to help reduce pilot disorientation by providing a gyro-stabilized straight luminous line across their field of view within the cockpit. In most configurations of the PVHD the line remains parallel with but displaced downward from the apparent location of the real world horizon. Theoretically, this line is supposed to provide useful pitch and roll orientation cues at an "unconscious" level of processing so as to permit ongoing central visual field processing as usual. The concept presented below is based partially on the PVHD concept and partially on more traditional head up display (HUD) design concepts (cf. Jenny et al., 1971).

An ultra wide field head up display is illustrated in Figure 27. Justifications for and details of this display are given elsewhere (Haines, 1984e). Shown here is a cockpit of the future where the crew is surrounded by a transparent "bubble" canopy which has the capacity of presenting computer-controlled symbology.

Figure 27

Artist's Conception of an Ultra-Wide Field Aircraft Head-up Display.



Data from Haines (1984b) and the present study may find application in the design and placement of symbology for an ultra-wide field HUD such as is illustrated above. For example, if pitch-related information should be presented in the far visual periphery, to help reduce the workload involved in information processing in the central visual field, then the present data is applicable. For example, by *lengthening* the line stimulus appropriately in the upper portion of the visual field or to either side of the line of sight, pitch discrimination sensitivity will be maintained at high levels. In the case of the vertical retinal meridian above the fovea, the data from Haines (1984b) has shown that a pilot can look down at his instrument panel (a vertical angle of about 30° from level) and still be able to perceive the vertical displacement of the distant horizon as small as 8 - 10 minutes of arc as long as the line stimulus is at least 17° arc long. Other such applications will be left up to the reader.

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APPENDIX A

Test Instructions

READ THESE INSTRUCTIONS CAREFULLY. FEEL FREE TO ASK ANY QUESTIONS TO BE SURE THAT YOU FULLY UNDERSTAND WHAT IS REQUIRED OF YOU.

"This is a study of how well you can discriminate very small movements of a single horizontal line that appears to be a great distance away. Your participation in this study is divided into two parts, an initial training and familiarization part and a data collection part. You will be told when training is complete. In addition, an experimenter will give you a detailed briefing on the operation of all equipment and how you are to respond. Be sure to ask questions if anything is not clear."

"Your tasks include: (1) following all instructions exactly about *where to fixate* (look steadily), (2) *which response toggle switches to use*, and (3) *striving for accuracy and not speed*. You will begin each trial yourself by moving a "NEXT TRIAL" toggle switch when you are ready to do so."

"During this study you are to look as steadily as possible at a small white dot at the center of of the screen directly in front of you. A white, horizontal stimulus line will be located at some distance away to the right of the dot, at the same level as the dot. If you should look away from the dot momentarily, try to look back at it as soon as you can."

"Two separate finger pressing responses are required. Before each is described it is necessary to describe the nature of the observing task. After a brief period of time this line will fall slowly downward to some new position. After it has remained in its new position for a second or so, it will disappear and then reappear at its original position. Then it will descend a second time and then stop for a second or so and disappear. Your first judgment is simply to *compare the two downward movements and decide on which trial the horizontal line dropped the most*, i.e., through the largest vertical angle. Pull the "number one" toggle switch toward you if you think it was the first of the two trials on which the line dropped the most. Use toggle "number two" if you think it was the second trial. It is absolutely necessary for you to make a choice on every pair of trials no matter how difficult the judgment may seem. In fact, the experiment will not proceed until you do select toggle "one" or "two". To help you locate these two toggle switches in the darkened laboratory, a small red light will appear just above each toggle switch."

"It is also important not to take into consideration anything you had seen on earlier trials in the experiment. That is, consider each pair of trials a small experiment by itself. What happened previously has *no bearing at all* on the current judgment."

"The second finger response you are to make is a confidence judgment. After completing the above judgment (using toggle "one" or "two") you will notice a row of nine small red lights come on above nine toggle switches on the left side of your response panel. Let toggle *"two"* represent *minimum confidence* that your previous judgment is correct. Let toggle "nine" represent 100 per cent confidence that your previous judgment is correct. Toggle "five" in the middle of the scale represent a "moderate amount of confidence." Based upon that criteria, you can pull any of the toggles between two and nine based upon your judgement. If you have to make a pure guess between toggle "one" and "two" then press toggle "1" during this confidence judgment period.

To summarize:

Toggle	Meaning
1	Pure guess
2	Minimum confidence
5	Medium confidence (mid scale)
9	100% (full) confidence

"After you have made your confidence response all nine red lights will go out leaving a red light on at the right end of the response panel. This light is labelled "N" which stands for *"Next Trial."* When you pull this toggle switch you will receive the next trial pair. Please pull the toggle toward you quickly and sharply. Do not hold it down at all."

"In order to help stabilize your viewing position during testing a padded head rest is used. It is important for you to try ***not to move your head during testing***. An experimenter will adjust your seat position for you and instruct you how to help in this. Other minor instructions will be given to you as necessary."

DO YOU HAVE ANY QUESTIONS?

APPENDIX B

Total Errors for Each Observer and Stimulus Image Position for the Variable Stimulus Length Condition.

Obs. No.	0°	2°	10°	30°	40°	50°	60°	70°	80°
1	0	2	1	1	1	2	2	2	4
2	1	2	0	0	0	0	2	2	5
3	0	2	0	2	0	0	1	1	2
4	0	2	3	2	0	0	1	5	3
5	0	3	0	4	0	2	2	4	3
6	1	4	0	3	0	2	1	5	2
7	1	2	1	3	0	1	2	6	7
8	0	2	0	2	1	2	1	3	2
9	0	2	0	3	1	0	2	1	5
10	0	0	3	4	2	3	3	4	7
11	0	2	2	6	1	4	5	6	6
12	0	2	3	4	3	3	5	5	7
13	0	2	2	5	1	2	4	5	1
14	4	3	4	3	5	4	1	2	4
15	1	2	1	3	0	0	4	4	4
16	1	1	2	1	1	6	1	1	5
17	1	0	0	3	0	1	3	0	4
18	0	6	1	3	0	5	4	4	6
19	1	2	0	2	0	0	1	2	2
20	0	2	0	3	0	0	1	4	4
21	1	2	0	6	0	1	4	4	4
22	1	4	2	1	0	0	0	4	6
23	0	1	1	0	2	1	1	1	2
24	1	1	2	0	0	2	0	1	5
$\bar{x}$	0.58	2.13	1.17	2.67	0.75	1.71	2.13	3.17	4.17
SD	0.88	1.26	1.24	1.69	1.23	1.73	1.51	1.79	1.79

APPENDIX C

Total Errors for Each Observer and Stimulus Image Position for the One Degree Stimulus Length Condition.

Obs. No.	0°	2°	10°	30°	40°	50°	60°	70°	80°
1	0	1	3	2	1	4	5	6	4
2	1	1	0	2	2	4	2	4	5
3	0	1	3	3	2	3	2	4	1
4	0	0	1	3	2	4	3	4	6
5	0	1	1	5	5	4	5	4	6
6	1	4	0	3	0	4	4	4	5
7	1	2	2	7	1	4	5	5	5
8	0	0	2	2	2	3	4	5	3
9	0	2	2	1	1	5	3	3	2
10	0	4	2	6	4	5	7	7	4
11	0	1	2	2	5	3	5	7	4
12	0	1	1	2	2	4	5	1	3
13	0	0	2	4	4	4	2	5	6
14	4	1	4	4	4	3	4	4	5
15	1	2	0	6	2	6	2	5	5
16	1	3	1	1	1	3	2	3	6
17	1	2	1	5	2	7	3	3	7
18	0	3	3	7	4	5	3	4	3
19	1	1	1	3	0	2	6	5	8
20	0	2	4	0	5	6	6	3	6
21	1	2	3	5	6	3	5	2	4
22	1	1	2	4	1	4	2	3	4
23	0	2	0	2	1	4	3	5	2
24	1	1	1	3	1	2	5	4	6
$\bar{x}$	0.58	1.58	1.71	3.42	2.42	4.00	3.88	4.17	4.58
SD	0.88	1.10	1.20	1.91	1.74	1.22	1.51	1.40	1.69

APPENDIX D

Total Errors in the Range of Confidence 2-9 for Each Observer and Stimulus Image Position for the Variable Stimulus Length Condition.

Obs. No.	0°	2°	10°	30°	40°	50°	60°	70°	80°
1	0	2	1	1	1	2	2	2	4
2	0	1	0	0	0	0	0	2	4
3	0	2	0	2	0	0	1	1	2
4	0	2	3	2	0	0	1	3	3
5	0	1	0	1	0	1	0	1	0
6	0	1	0	0	0	1	0	4	1
7	1	2	1	3	0	1	1	3	5
8	0	2	0	2	0	2	0	3	1
9	0	0	0	2	1	0	1	1	4
10	0	0	2	3	2	3	1	3	4
11	0	1	1	3	0	2	5	4	3
12	0	1	1	1	0	1	4	3	2
13	0	1	2	5	1	1	3	1	0
14	2	1	1	2	4	3	1	2	3
15	0	1	1	2	0	0	4	1	3
16	1	0	1	0	0	2	0	1	1
17	1	0	0	3	0	1	3	0	5
18	0	3	0	1	0	2	0	2	1
19	0	1	0	0	0	0	0	1	1
20	0	0	0	0	0	0	0	0	1
21	0	1	0	4	0	0	1	3	2
22	1	2	1	1	0	0	0	2	3
23	0	1	1	0	2	1	0	0	0
24	1	0	1	0	0	0	0	0	0
$\bar{x}$	0.29	1.08	0.71	1.58	0.46	0.96	1.17	1.79	2.21
SD	0.55	0.83	0.81	1.41	0.98	1.00	1.52	1.25	1.62

APPENDIX E

Total Errors in the Range of Confidence 2-9 for Each Observer and Stimulus Image Position for the One Degree Stimulus Length Condition.

Obs. No.	0°	2°	10°	30°	40°	50°	60°	70°	80°
1	0	1	3	2	0	4	5	6	4
2	0	1	0	2	2	3	2	4	4
3	0	1	2	2	1	1	1	4	0
4	0	0	1	2	2	2	3	4	6
5	0	0	0	0	2	2	2	1	1
6	0	1	0	1	0	2	2	2	3
7	1	2	2	6	0	0	0	2	0
8	0	0	1	2	1	1	2	1	0
9	0	1	0	1	1	2	2	0	0
10	0	4	2	3	2	4	5	5	2
11	0	1	2	2	4	1	4	3	3
12	0	0	1	1	1	2	2	0	0
13	0	0	1	3	2	4	0	2	1
14	2	1	3	2	3	2	3	3	3
15	0	2	0	2	1	5	0	5	0
16	1	0	1	0	0	2	1	1	3
17	1	2	1	4	2	5	3	3	1
18	0	2	0	1	2	0	2	0	2
19	0	1	1	1	0	1	2	1	2
20	0	1	0	0	1	2	0	0	0
21	0	0	2	1	1	1	1	0	1
22	1	0	2	2	0	2	1	0	2
23	0	1	0	1	0	1	0	0	0
24	1	1	0	0	1	0	1	2	1
$\bar{x}$	0.29	0.96	1.04	1.71	1.21	2.04	1.83	2.04	1.82
SD	0.55	0.96	1.00	1.37	1.06	1.46	1.46	1.88	1.64

APPENDIX F

Total Guesses for Each Observer and Stimulus Image Position for the Variable Stimulus Length Condition.

Obs. No.	0°	2°	10°	30°	40°	50°	60°	70°	80°
1	0	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	2	0	1
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	2	0
5	0	2	0	3	0	1	2	3	3
6	1	3	0	3	0	1	1	1	1
7	0	0	0	0	0	0	1	3	2
8	0	0	0	0	1	0	1	0	1
9	0	2	0	1	0	0	1	0	1
10	0	0	1	1	0	0	2	1	3
11	0	1	1	3	1	2	0	2	3
12	0	1	2	3	3	2	1	2	5
13	0	1	0	0	0	1	1	4	1
14	2	2	3	1	1	1	0	0	1
15	1	1	0	1	0	0	0	3	1
16	0	1	1	1	1	4	1	0	4
17	0	0	0	0	0	0	0	0	0
18	0	3	1	2	0	3	4	2	5
19	1	1	0	2	0	0	1	1	1
20	0	2	0	3	0	0	1	4	3
21	1	1	0	2	0	1	3	1	2
22	0	2	1	0	0	0	0	2	3
23	0	0	0	0	0	0	1	1	2
24	0	1	1	0	0	2	0	1	5
$\bar{x}$	0.29	1.04	0.46	1.08	0.29	0.75	0.96	1.38	2.00
SD	0.55	0.96	0.78	1.21	0.69	1.11	1.04	1.31	1.62

APPENDIX G

Total Guesses for Each Observer and Stimulus Image Position for the One Degree Stimulus Length Condition.

Obs. No.	0°	2°	10°	30°	40°	50°	60°	70°	80°
1	0	0	0	0	1	0	0	0	0
2	1	0	0	0	0	1	0	0	1
3	0	0	1	1	1	2	1	0	1
4	0	0	0	1	0	2	0	0	0
5	0	1	1	5	3	2	3	3	5
6	1	3	0	2	0	2	2	2	2
7	0	0	0	1	1	4	5	3	5
8	0	0	1	0	1	2	2	4	3
9	0	1	2	0	0	3	1	3	2
10	0	0	0	3	2	1	2	2	2
11	0	0	0	0	1	2	1	4	1
12	0	1	0	1	1	2	3	1	3
13	0	0	1	1	2	0	2	3	5
14	2	0	1	2	1	1	1	1	2
15	1	0	0	4	1	1	2	0	5
16	0	3	0	1	1	1	1	2	3
17	0	0	0	1	0	2	0	0	6
18	0	1	3	6	2	5	1	4	1
19	1	0	0	2	0	1	4	4	6
20	0	1	4	0	4	4	6	3	6
21	1	2	1	4	5	2	4	2	3
22	0	1	0	2	1	2	1	3	2
23	0	1	0	1	1	3	3	5	2
24	0	0	1	4	0	2	4	2	5
$\bar{x}$	0.29	0.63	0.67	1.75	1.21	1.96	2.04	2.12	2.96
SD	0.55	0.92	1.05	1.73	1.28	1.20	1.65	1.57	1.94

CONTRAST SENSITIVITY: RELATING VISUAL AND DISPLAY CAPABILITY TO PERFORMANCE

Arthur P. Ginsburg, Ph.D.

Vision Research Laboratory
Vistech Consultants, Inc.
Dayton, Ohio

BIOGRAPHY

Dr. Arthur P. Ginsburg holds a B.S. in Systems Engineering from Widener College, and M.S. in Bioengineering from the Air Force Institute of Technology, and a Ph.D. in Biophysics from the University of Cambridge, England. During his career in the Air Force, he founded the Aviation Vision Lab, serving as Director and Principal Investigator. Currently Dr. Ginsburg is the Director of Research and Development of Vistech Consultants, Inc., of Dayton, Ohio, as well as an Adjunct Associate Professor of Psychology at Wright State University. A correspondent-at-large and a working member on Emerging Visual Techniques for the National Committee on Vision, Dr. Ginsburg also serves internationally as the consultant for Visual Performance to the Commission Internationale de E'Clairage (CIE).

Dr. Ginsburg pioneered the application of basic vision research on a human vision model along with relating contrast sensitivity to new performance-based vision tests. Furthermore, he conducted the initial research showing that individual contrast sensitivity quantifies visual capability in the detection and identification of targets under both simulated and actual conditions. His invention of a chart system able to provide fast, accurate contrast sensitivity functions is changing the field of vision today. Dr. Ginsburg lectures extensively both nationally and abroad, and is the author of many articles and papers in professional journals on the subjects of basic and applied vision.

Dusk is falling over the mountainous terrain, the icy rain is showing no signs of abatement, and the Air Force pilot is doing his best ot maintain complete control of the F-16. Between the environmental conditions and the stress of straining to clearly see the data in the heads-up display, though, this pilot is becoming fatigued. While little can be done about the surroundings, the pilot's visual capability, the HUD system and their relationship to the pilot's safety and success merits examination. This paper provides a review of research that uses contrast sentitivity technology to provide new metrics of visual and display quality [1].

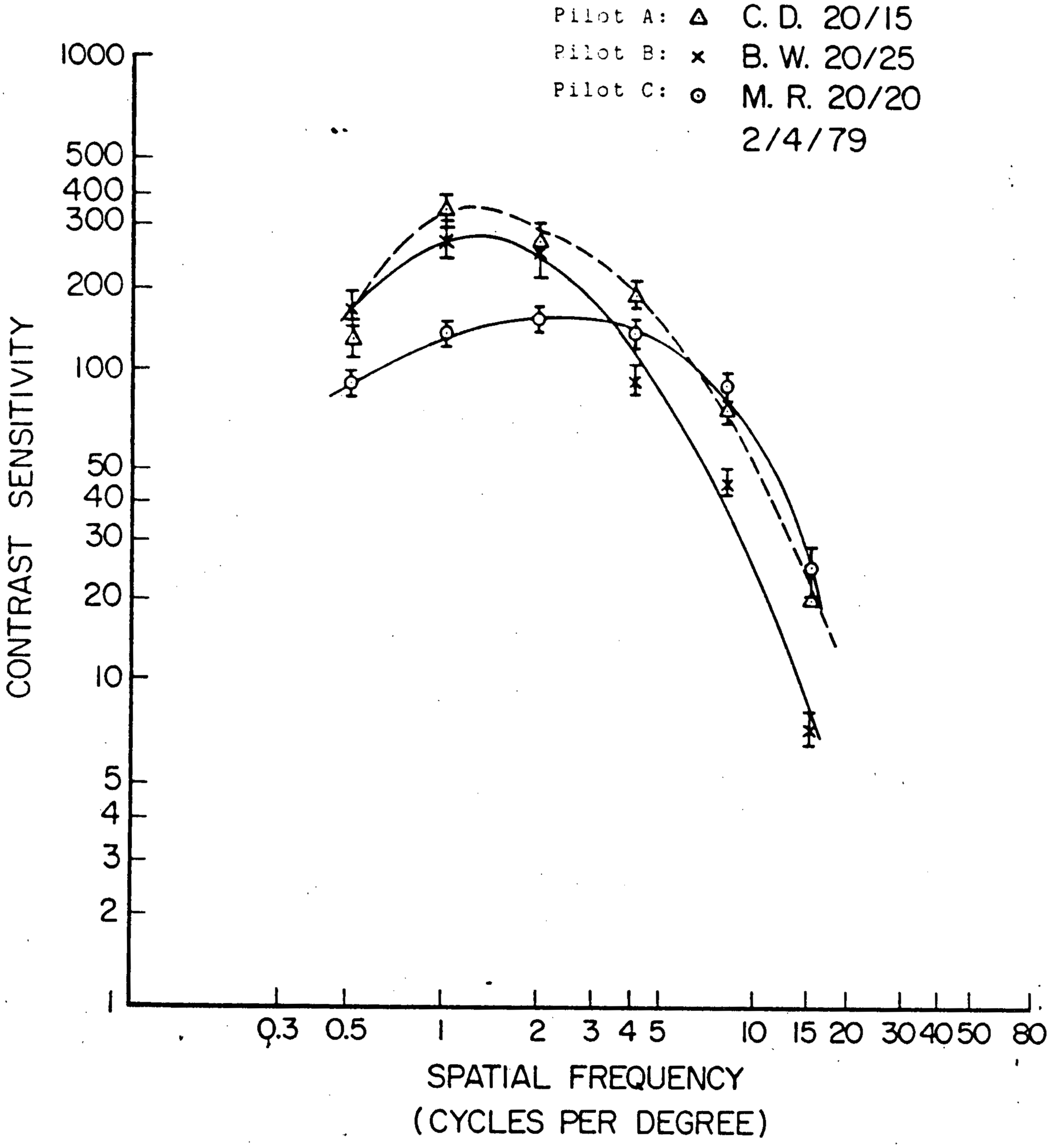

Figure 1: The contrast sensitivity functions of three pilots. Even though pilot C has 20/20 acuity, his contrast sensitivity to larger objects at 0.5 - 3 cycles per degree is lower than pilot B having lower acuity. Studies have shown that pilot B will detect and identify large targets better than pilot C.

Contrast Sensitivity and Visual Performance

Vision standards for pilots are based on their ability to see high contrast black-and-white targets on an eye chart. Current vision science provides evidence of the serious limitations of present eye charts to measure visual health or performance capability [2]. Just as hearing tests use tones of different loudness and sound frequencies to test auditory cells tuned to different ranges of sound, modern vision tests must use targets of different contrasts and spatial frequencies or sizes to test visual cells tuned to different sizes. Sine-wave gratings, not letters or disks, are used as test targets for two major reasons. First, any complex target can be described by a combination of sine-wave gratings having different amplitudes and orientations. Secondly, sine-wave gratings are the most sensitive vision test targets [3,4].

The result of testing visual threshold contrast to sine-wave gratings is a contrast sensitivity curve. Contrast sensitivity curves can vary between individuals [5,6], as shown in Figure 1. These kinds of differences in contrast sensitivity between pilots have been shown to relate to target detection range in flight simulators [7] (Figure 2) and in field trails [8]. For example, the average difference in detection range distance in the field trails was 1.96 miles; average detection time difference was 56 seconds. These large differences occured even though all pilots had acuity of 20/20 or better. Clearly, those kind of data warrant serious consideration of contrast sensitivity as a vision standard [2,6].

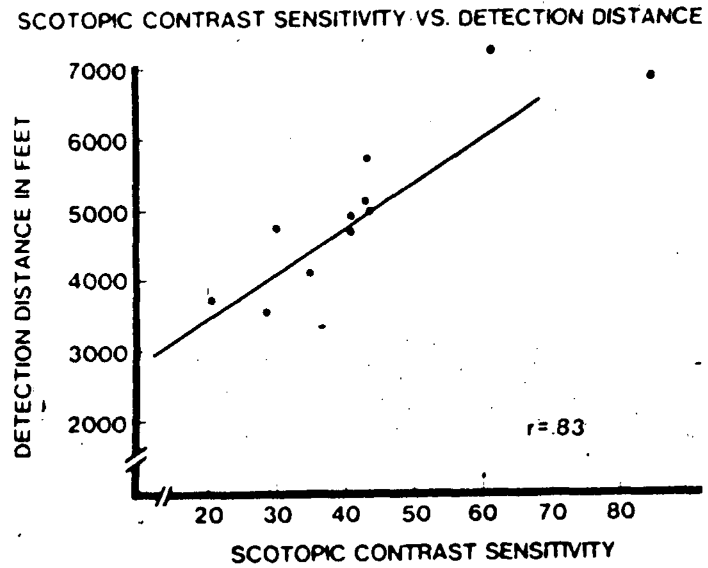

Figure 2: Data showing the relationship between contrast sensitivity and acuity to pilot detection range in a flight simulator. There is a nonsignificant negative correlation between the visual acuity of the pilots and detection range. There is a significant positive correlation between the peak contrast sensitivity of the pilots and detection range.

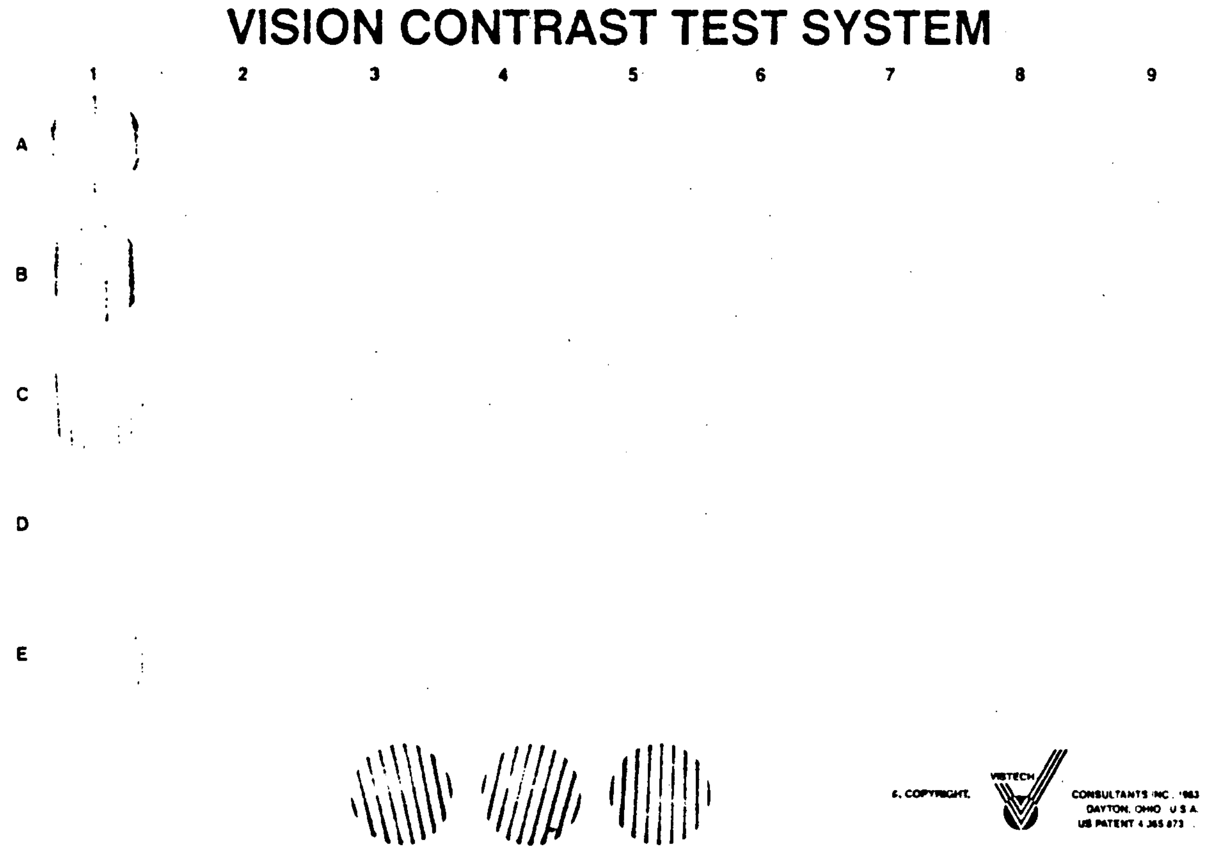

Figure 3: The Vision Contrast Test System (VCTS). The observer reports the orientation of the last striped patch for each line (spatial frequency). The correct response is plotted for each line to create a contrast sensitivity curve. The test takes less than one minute.

Will new vision standards based on contrast sensitivity keep more pilots out of the cockpit that visual acuity? The answer appears to be no. If contrast sensitivity criterion were used on present pilots rather than acuity, more would probably remain in the cockpit [2]. Acuity has never been shown to relate well to visual performance. The recent studies reported here further support earlier findings. Therefore, other than historical precedent, why should acuity be used as the standard for determining pilot visual capability? This is an especially important question when research shows that the peak of the contrast sensitivity function is more important for pilot visual performance than are the highest spatial frequencies, which relate to 20/20 acuity [7,8]. Contrast sensitivity may provide a more rational basis for deciding whether to train a pilot candidate; whether to have a pilot fly a tanker, transporter, bomber, or the higher-performance attack or reconnaissance aircraft; as well as whether age or eye damage has reduced visual capability significantly to affect pilot performance. Now that research has shown how visual capability can be related to pilot performance, it is reasonable to begin a program incorporating contrast sensitivity into the pilot selection process and creating operationally-relevant vision standards, in order to optimize flying safety and performance. With the creation of a new contrast sensitivity chart, shown in Figure 3, contrast sensitivity testing can easily, quickly, and inexpensively be accomplished by the clinician's aide [9.10].

Contrast Sensitivity and Display Quality

Contrast sensitivity technology is not just for testing vision; it is also proving useful for evaluating display quality [11]. Head-up displays (HUDs), which allow the pilot to simultaneously see main targets and aircraft data, are increasing in use. Although see-through visibility is a primary desired characteristic, many conventional HUD systems have visibility quotients of only 50 to 70%. Losses in visibility can be attributed to several factors; among them, light scattering, glare, reflections, and transmission. Unfortunately, just as in the practice of measuring acuity, direct measurements of those factors have not exhibited a direct relationship to pilot performance and resultant visual capability. Therefore, a more general approach is needed.

Analytical throughput is the ability to characterize applicable target data in the same language used to designate system capability, visual processes, and performance metrics such as detection range. Without analytical throughput, the process of specifying display metrics is considerably limited. In spite of this, a system of performance-based metrics may be developed utilizing linear systems analysis and the growing knowledge about vision.

The relatively new area of contrast sensitivity provides singular promise for detection range correlation. First, sine-wave gratings imaged through a display system produce a contrast sensitivity function to which detection range can be correlated [8]. Regions in the contrast sensitivity function relate to the spatial frequency bandwidth of pertinent target information. Since the contrast sensitivity function may then be linked to losses in target contrast and detection range, this measure is applied to the problem of HUD optics and their individual general qualities.

In summary, the present metric standards used for evaluation unsatisfactorily test the HUD units. Even with specifications that meet the requirements for given aspects (i.e. optical transmission), pilot complaints of optical problems are still frequent. Consideration of only the component of optical transmission excludes other critical factors, such as target visibility, glare, and light scatter.

The contrast sensitivity function of the HUD can be used as an indicator of the HUD's ability to transmit target contrast information. The observer's contrast sensitivity is measured while viewing through the HUD. This information determines the visual contrast sensitivity of the HUD. Thus, the observer functions as a contrast detector, providing baseline values for other testing conditions. Similar to standard contrast sensitivity testing, the contrast sensitivity function measurements are performed with a microprocessor-controlled portable computer or photographic plates [13]. The gain or loss of threshold contrast for the HUD is the contrast sensitivity difference between the observation of gratings around and through the HUD.

A recent study used contrast sensitivity to test HUDs [12]. To test the contrast sensitivity of the head-up displays under laboratory conditions, a constant lighting environment was created. Sky conditions of a bright but cloudy day were then simulated. Lights other than those used in the simulator were turned-off in order to evaluate contrast sensitivity losses caused by transmission losses of the HUD optics. Three HUD units were used in this study: AFTI, Production, and LANTIRN. These three systems were then evaluated under three contrast sensitivity conditions: baseline CS without the HUD, CS through the center of the lower HUD, and through the center of the eyebrow. The eyebrow condition was performed only on the AFTI and LANTIRN units. High and low luminance levels were imposed during the testing. For all HUDs, visor-up and visor-down results were recorded.

Comparable spatial frequency losses in contrast sensitivity were produced during the lights-off phase. From this, it can be inferred that corresponding losses in transmission resulted. In addition, losses for all spatial frequencies for each of the HUDs indicated similar light scatter, glare and reflection casual factors during the lights-on condition. Both the AFTI and

LANTIRN eyebrown measurements exhibited significant decreases in contrast sensitivity. For average viewing conditions, no important differences in contrast sensitivity were detected. Finally, the largest high spatial frequency losses were incurred in the visor-down state.

Further examination of the relationship of contrast sensitivity to HUD systems required evaluation under real-world luminance conditions. To provide for the greatest degree of accuracy in the results, comparisons to the laboratory data were needed. As with the previous experiments, three HUDs; the AFTI, Production, and LANTIRN; were used. The three F-16 aircrafts containing the HUDs were parked perpendicularly to the sun's path at zenith. This was done to prevent "sunspots" which could affect one or more of the HUDs, possibly resulting in unreliable data. Accordingly, the contrast sensitivity measurements were completed between sunrise and sun-zenith. Canopy reflections were eliminated using opaque black cloth taped to the canopies. Uniformity of results was ensured by using the same pilots from the laboratory experiments. Further coherence was achieved with simultaneous measurements of the three HUD contrast sensitivity levels. Here again, the readings were taken in these positions: baseline CS without the HUD, CS through the center of the lower HUD, and through the center of the eyebrow for the AFTI and LANTIRN HUDs.

The results of these tests showed greater contrast sensitivity losses for the LANTIRN and Production HUDs where contrast sensitivity was measured in the center of the HUDs and for average viewing conditions. The largest contrast sensitivity losses measured in the eyebrow were from the AFTI, HUD, for the higher spatial frequencies. Factors relevant to the losses were glare and transmission. Losses in the eyebrow measurements at the lower spatial significant frequencies were noted with the LANTIRN HUD, due to reflections. The small but important contrast sensitivity differences seen in field conditions but not in the laboratory reflect composites of opposite interactions of several HUD losses in the field.

Evaluation of the HUD units centers primarily on the measurement of some of the systems elements, including limiting resolution, transmission loss, and the number of gray shades. However, since these factors exhibit little relation to real-world performance capability, a better method of appraisal is required. Accordingly, contrast sensitivity measurements provide for direct, relation of target information to display capability and pilot performance.

Target contrast and detection range are dependent on changes in the contrast sensitivity of the display and observer. The results of the trials previously discussed confirm the usefulness of contrast sensitivity functions to practical applications in heads-up displays. Although these tests were limited to specific conditions, the results indicate the need for further consideration as to visibility losses in HUD units. Moreover, since these decreased visibility losses in the HUDs increase the workload and detection times for pilots, the responsibility for the safety and success of a pilot on a given mission depends, in part, on the HUD. Six to eight percent was the average detection penalty for the HUDs tested here, although the HUDs tested were of three different types. In conclusion, the contrast sensitivity evaluations for both pilots and HUDs have been shown to be meaningful for safety and performance reasons.

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VISUAL AND VESTIBULAR MECHANICS OF SPATIAL DISORIENTATION

by

Kent K. Gillingham, M.D., Ph.D.
Crew Technology Division
USAF School of Aerospace Medicine
Brooks AFB, TX 78235-5301

BIOGRAPHY

Kent Gillingham was born in Bad Axe, Michigan, on 16 July 1938, and grew up in Midland and Ann Arbor, Michigan. He graduated from Ann Arbor High School in 1956, and attended the University of Michigan College of Literature, Science and Arts before entering the University of Michigan Medical School in 1959. While in medical school, he developed interests in both medical research and aviation; and as a National Science Foundation Fellow in 1961, he began his research in vestibular mechanisms. Upon graduation from medical school in 1963, he reported for military duty at USAF Hospital Wright-Patterson, where he did his internship. He then went to the USAF School of Aerospace Medicine to take the Aerospace Medicine Primary course, and remained there from 1964 to 1967 as a flight surgeon engaged in research and teaching in the field of vestibular physiology, spatial disorientation, and motion sickness. During the same period, he continued his civilian pilot training, obtaining a commercial pilot license with multiengine and instrument ratings. Upon completion of his Air Force commitmemt, he joined the faculty of the University of Iowa College of Medicine as Assistant Professor of Otolaryngology. In that position, he conducted vestibular research, teaching, and clinical evaluation of patients with vertigo. In 1969, Dr. Gillingham resumed his academic training, entering the University of Iowa Graduate College as a Special Research Fellow of the National Institutes of Health. After obtaining a Ph.D. in Physiology and Biophysics in 1973, he returned to the School of Aerospace Medicine as a research medical officer in the Crew Technology Division, where he has been primarily occupied with high-G research, teaching, and aeromedical evaluation using the USAFSAM human centrifuge. His major interests and efforts have been in quantifying acceleratory stresses of flight, determining the physiologic and pathologic responses to high-G stress, and training aircrew to recognize the hazards of high-G stress and employ proper means of preventing G-induced loss of consciousness in flight. He has recently become involved again in spatial disorientation research and teaching, and has been engaged in the development of ground-based devices for demonstrating to aircrew the effects of spatial disorientation in flight.

Dr. Gillingham is a member of the Aerospace Medical Association, the Aerospace Physiologist Society, Life Sciences and Biomedical Engineering Branch, and Space Medicine Branch constituent organizations. He received the

Arnold B. Tuttle and Harry G. Moseley awards of the Aerospace Medical Association in 1977 and 1984, respectively, and was elected a Fellow of the Aerospace Medical Association in 1980. He is also a member of the Phi Beta Kappa and Alpha Omega Alpha honor societies, and the Sigma Xi scientific research society. His publications include 29 scientific papers and six textbook chapters of which he is first author, and 10 scientific articles of which he is co-author. Dr. Gillingham lives with his wife, Janet, and their four children on a small ranch near Floresville, Texas. Working on the ranch, playing basketball, and flying his Cessna 210 are his principal avocations. Dr. Gillingham has been a private pilot for many years and has owned several aircraft, including a T-6, Cessna 180, 182, and 185.

The evolution of man saw him develop over millions of years as an aquatic, terrestrial, and even arboreal creature, but never an aerial one. In this development he subjected himself to, and was subjected to, many different varieties of transient motions, but not to the relatively sustained linear and angular accelerations commonly experienced in aviation. As a result, he acquired sensory systems well suited for maneuvering under his own power on the surface of the earth but poorly suited for flying. Even the birds, whose primary mode of locomotion is flying, are unable to maintain spatial orientation and fly safely when deprived of vision by fog or cloud. Only bats seem to have developed the ability to fly without vision, and then only by replacing vision with auditory echolocation. Considering man's phylogenetic heritage, we should not be surprised that his sudden entry into the aerial environment results in a mismatch between the orientational demands of the new environment and his innate ability to orient. The manifestation of this mismatch is spatial disorientation.

ILLUSIONS IN FLIGHT

An illusion is a false percept. An *orientational illusion* is a false percept of one's position, attitude, or motion, relative to the plane of the earth's surface. Thus, misperceptions of displacement, velocity, or acceleration--either linear or angular--result in orientational illusions. A great variety of orientational illusions occur during flight: some named, some unnamed; some understood, some not understood. Those that are sufficiently impressive to cause pilots to report them, whether because of their repeatability or because of their emotional impact, have been described in the aeromedical literature, and will be discussed here. We categorize the illusions in flight into those resulting primarily from visual misperceptions and those involving primarily vestibular errors.

Visual Illusions. There are two different modes of visual processing, the focal (foveal) mode and the ambient (peripheral) mode. Generally speaking, focal vision is concerned with object recognition and ambient vision is concerned with spatial orientation. But some visual orientation tasks in flying--e.g., approach to landing--require a great deal of focal vision, and such tasks can be made extremely difficult by illusions resulting from misinterpretation of focal visual cues. The *runway illusions* and *approach illusions* are illustrative of this.[1]

Figure 1a shows the pilot's view of the runway during an approach to landing, and demonstrates the linear perspective and foreshortening of the runway that the pilot associates with a 3-degree approach slope. If the runway slopes upward 1 degree (a rise of only 35 m in a 2-km runway), the foreshortening of the runway for a pilot on a 3-degree approach slope is substantially less (the height of the retinal image of the runway is greater) than it would be if the runway were level. This can give the illusion of being too high on the approach. The pilot's natural response to such an illusion is to reshape his image of the runway by seeking a shallower approach slope (Fig. 1b). This response, of course, could be hazardous. The opposite situation results when the runway slopes downward. To perceive the accustomed runway shape under this condition, the pilot must fly a steeper approach slope than usual (Fig. 1c).

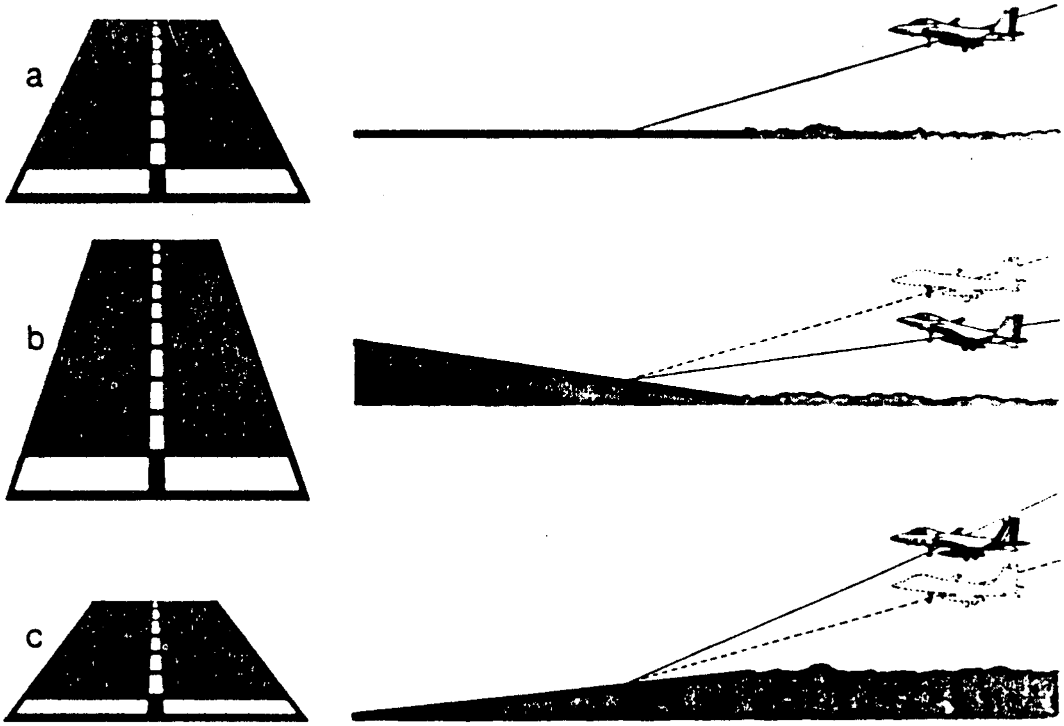


Figure 1. Effect of runway slope on pilot's image of runway during final approach (left), and potential effect on approach slope angle flown (right). a. Flat runway --normal approach. b. Upsloping runway creates illusion of being high on approach--pilot flies approach too low. c. Downsloping runway has opposite effect.

A runway that is narrower than that to which a pilot is accustomed can also create a hazardous illusion on the approach to landing. The pilot tends to perceive the narrow runway to be longer and farther away (i.e., that he is higher) than is actually the case, and he may flare too late and touch down sooner than he expects (Fig. 2b). Likewise, a runway that is wider than what a pilot is used to can lead him to believe he is closer to the runway (i.e., lower) than he really is, and he may flare too soon and drop in from too high above the runway (Fig. 2c). Both of these runway-width illusions are especially troublesome at night, when peripheral visual orientation cues are largely absent. The very common tendency for pilots to flare too high at night results at least partly from the fact that the runway lights, being displaced laterally from the actual edge of the runway, make the runway seem wider, and therefore closer, than it actually is.

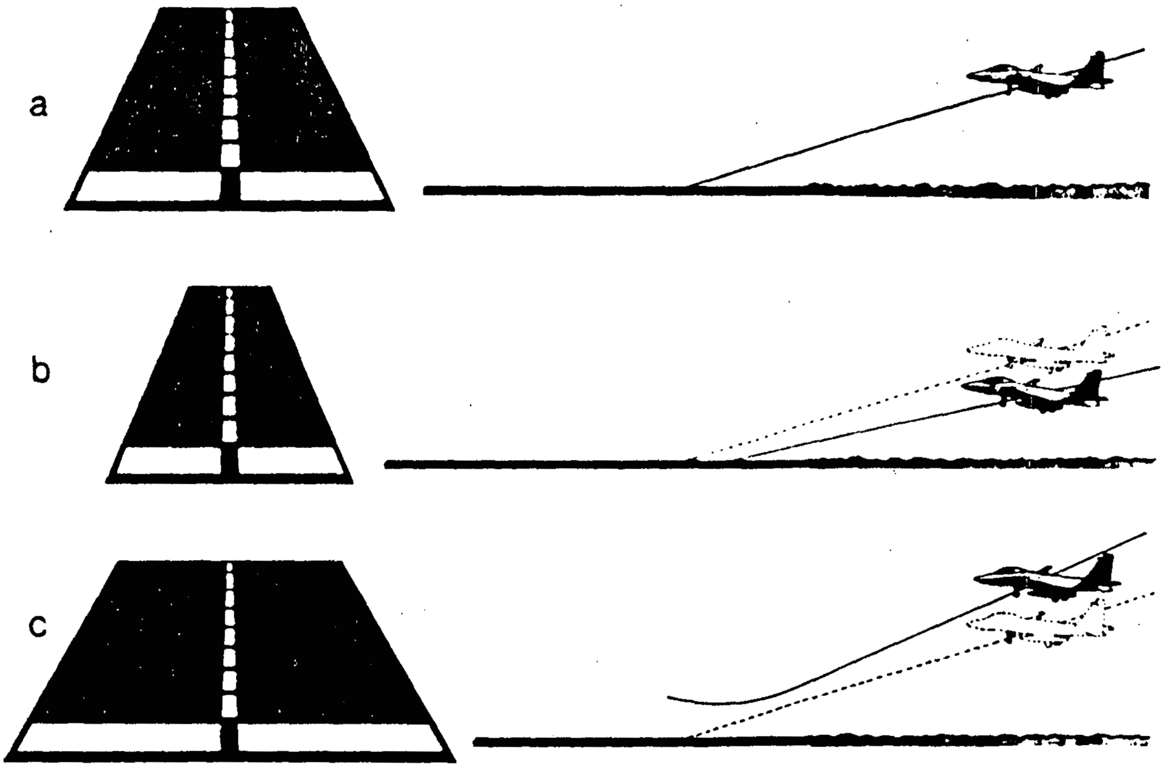


Figure 2. Effect of runway width on pilot's image of runway (left) and potential effect on approach flown (right). a. Accustomed width--normal approach. b. Narrow runway makes pilot feel he is higher than he actually is, so he flies approach too low and flares too late. c. Wide runway appears closer than it actually is--pilot tends to approach too high and flare too soon.

The slope and composition of the terrain under the approach path can also influence the pilot's judgment of his height above the touchdown point. If the terrain descends to the approach end of the runway, the pilot tends to fly a steeper approach than he would if the approach terrain were level (Fig. 3a). If the approach terrain slopes up to the runway, on the other hand, the pilot tends to fly a less steep approach than he would otherwise (Fig. 3b), Although estimation of height above the approach terrain depends on both focal and ambient vision, the contribution of focal vision is particularly clear: consider the pilot who looks at a building below him, and seeing it to be closer than such buildings usually are, he seeks a higher approach slope. By the same token, focal vision and size constancy are responsible for poor height and distance judgments pilots sometimes make when flying over terrain having an unfamiliar composition (Fig. 4). A reported example of this is the tendency to misjudge approach height when landing in the Aleutians, where the evergreen trees are much smaller than those to which most pilots are accustomed. Such height-estimation difficulties are by no means restricted to the approach and landing phases of flight. One fatal mishap occurred during air combat training over the Southwest Desert, when the pilot of a high-performance fighter apparently misjudged his height over the desert floor because of the small, sparse vegetation, and was unable to arrest in time his deliberate descent to a ground-hugging altitude.

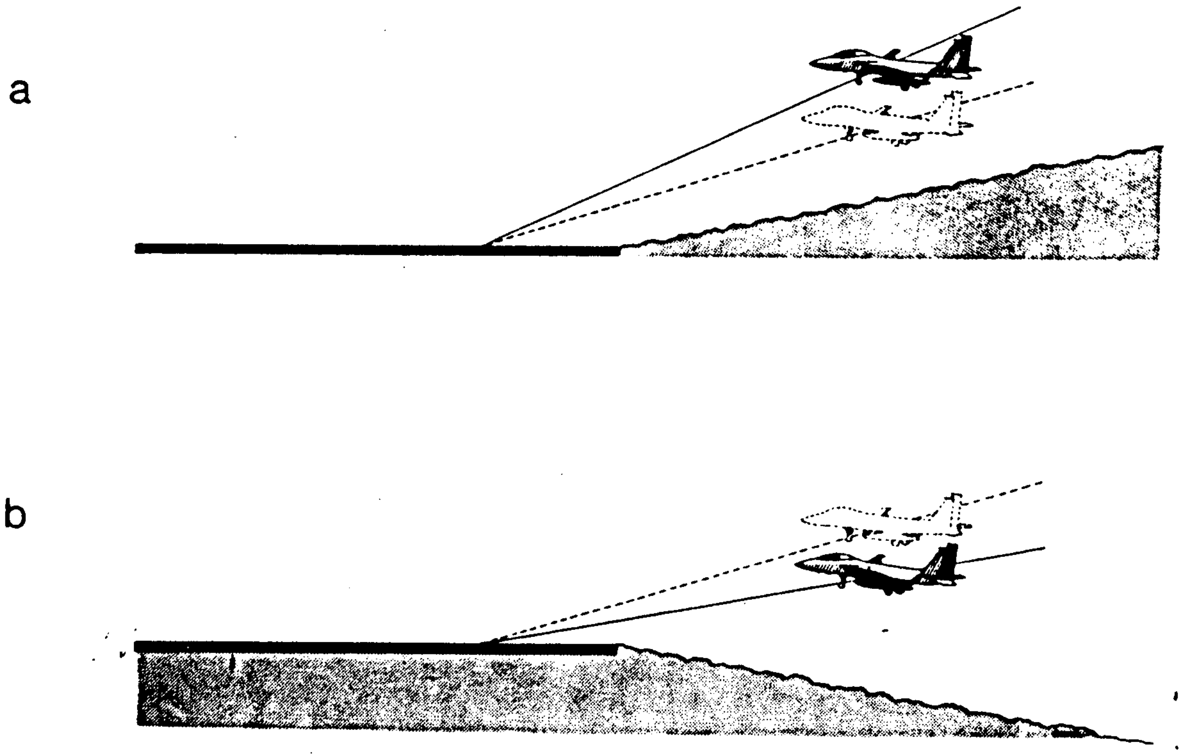


Figure 3. Potential effect of slope of terrain under the approach on approach slope flown. a. Terrain slopes down to runway; pilot perceives himself to be too shallow on approach and steepens it. b. Upsloping terrain makes pilot think he is too high, so he corrects by making approach too shallow.

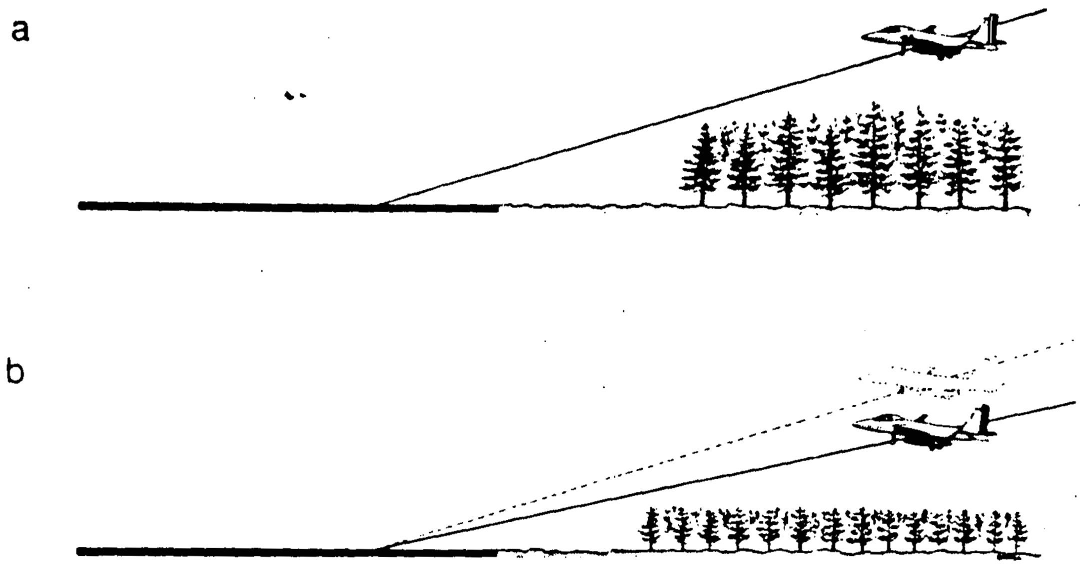


Figure 4. Potential effect of unfamiliar composition of approach terrain on approach slope flown. a. Normal approach over trees of familiar size. b. Unusually small trees under approach path make pilot think he is too high, so he makes his approach lower than usual.

A well-known pair of approach-to-landing situations that create illusions because of the absence of adequate focal visual orientation cues are the *smooth-water* (or *glassy-water*) and *snow-covered* approaches. A seaplane pilot's perception of height is degraded substantially when the water below is still: for that reason he routinely just sets up a safe descent rate and waits for the seaplane to touch down, rather than attempting to flare to a landing, when the water is smooth. A blanket of fresh snow on the ground also deprives the pilot of visual cues with which to estimate his height, thus making his approach more difficult--extremely difficult if the runway is also covered with snow. Again, approaches are not the only regime in which smooth water and fresh snow cause problems. A number of aircraft have crashed as a result of pilots' maneuvering over smooth water or snow-covered ground and misjudging their height above the water or ground.

In daytime, fog or haze can make a runway appear farther away as a result of the loss of visual discrimination. At night, runway and approach lights in fog or rain appear less bright than they do in clear weather, and can create the illusion that they are farther away. It has even been reported that a pilot can have an illusion of banking to the right, for example, if the runway lights are brighter on the right side of the runway than they are on the left. Another hazardous illusion of this type can occur during approach to landing in a shallow fog or haze, especially during a night approach. The vertical visibility under such conditions is much better than the horizontal visibility, so that descent into the fog causes the more distant approach or runway lights to diminish in intensity, at the same time that peripheral visual cues are suddenly occluded by the fog. The result is an illusion that the aircraft has pitched up, with the concomitant danger of a nose-down corrective action by the pilot.

Another condition in which a pilot is apt to make a serious misjudgment is in closing on another aircraft at high speed. When he has numerous peripheral visual cues by which to establish his own position and velocity relative to the earth and the target's position and velocity relative to the earth, his tracking and closing problem is not much different from what it would be on the ground if he were giving chase to a moving quarry. But when relative position and closure rate cues must come from foveal vision alone, as is generally the case at altitude, at night, or under other conditions of reduced visibility, the tracking and closing problem is much more difficult. An overshoot--or worse, a midair collision--can easily result from the perceptual difficulties inherent under such circumstances, especially when the pilot lacks experience in the environment devoid of peripheral visual cues.

Two runway approach conditions that create considerable difficulty for the pilot, and which, like the closure-rate problems discussed above, result from tasking focal vision to accomplish by itself what is normally accomplished with both focal and ambient vision, are the black-hole and whiteout approaches. A black-hole approach is one that is made on a dark night over water or unlighted terrain to a runway beyond which the horizon is indiscernible, the worst case being when only the runway lights are visible (Fig. 5). Without peripheral visual cues to help him orient himself relative to the earth, the pilot tends to feel he is stable and situated appropriately, but that the runway itself moves about or remains malpositioned (is downsloping, for example). Such illusions make the black-hole approach difficult and dangerous, and often result in a landing far short of the runway. A particularly hazardous type of black-hole approach is one made under conditions wherein the earth is totally dark except for the runway and the lights of a city on rising terrain beyond the runway. It has been observed that under these conditions the pilot tries to maintain a constant vertical visual angle for the distant city lights, thus causing his aircraft to arc far below the intended approach slope as he gets closer to the runway (Fig. 6).[2] An alternative explanation is that the pilot falsely perceives through ambient vision that the rising terrain is flat, and he lowers his approach slope accordingly.

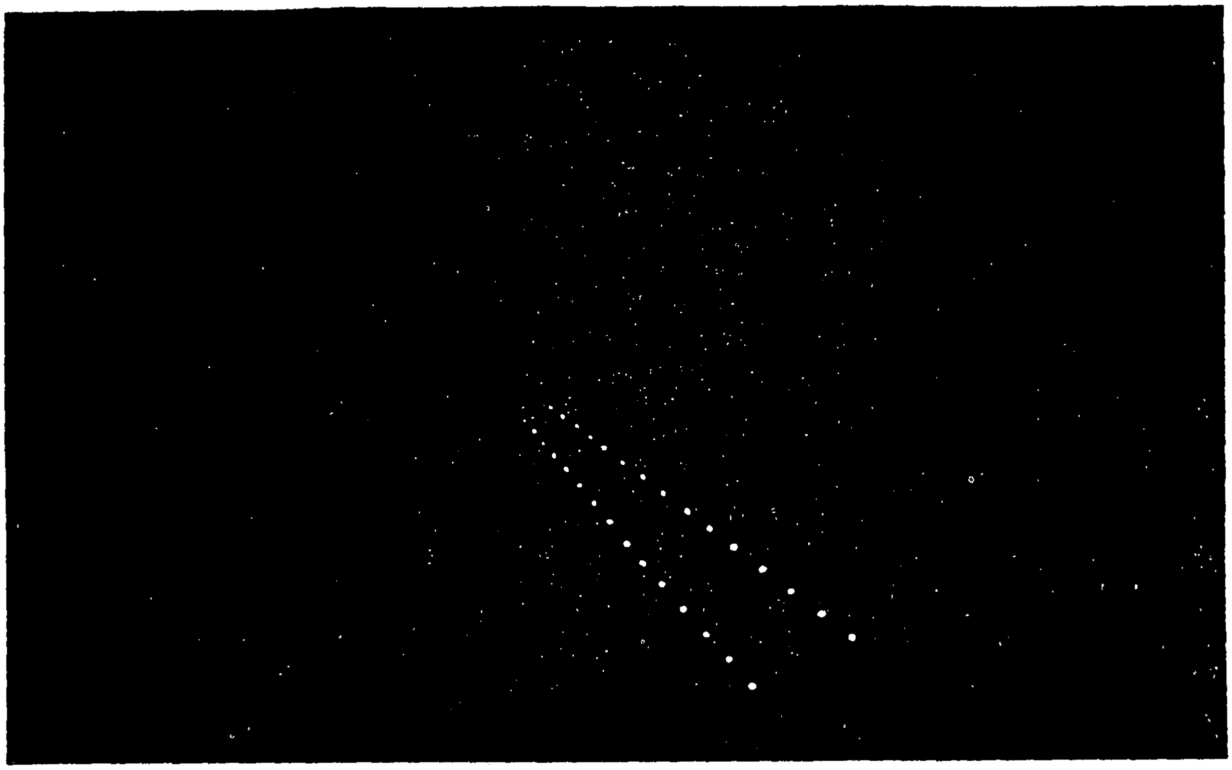


Figure 5. Effect of loss of peripheral visual orientation cues on perception of runway orientation during a black-hole approach. Above: When peripheral visual orientation cues are absent, pilot feels upright and (in this example) perceives runway to be tilted left and upsloping. Below: With horizon visible, pilot orients himself correctly with peripheral vision and runway appears horizontal in central vision.

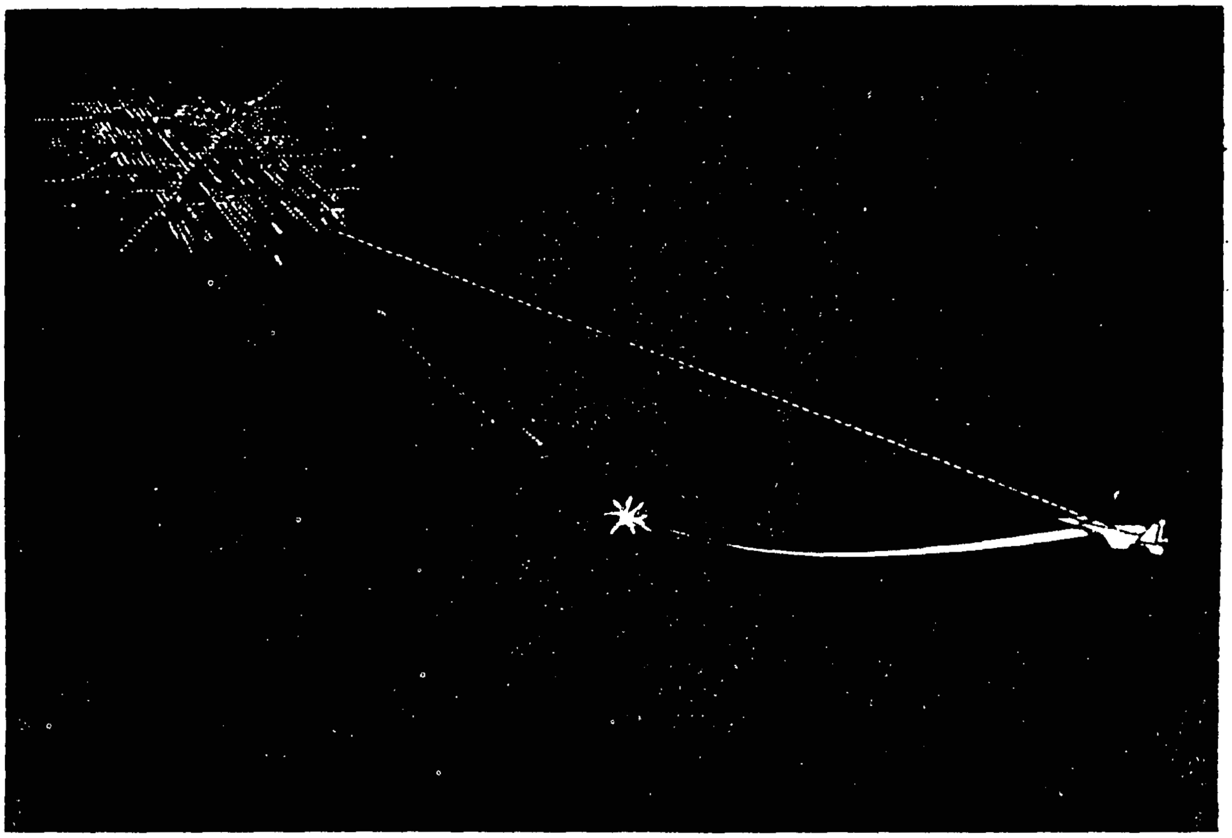


Figure 6. A common and particularly dangerous type of black-hole approach, in which pilot perceives distant city to be flat and arcs below desired approach slope.

An approach made under whiteout conditions can be as difficult as a black-hole approach, and for essentially the same reason--lack of sufficient ambient visual orientation cues. There are actually two types of whiteout, the atmospheric whiteout and the blowing-snow whiteout. In the atmospheric whiteout, a snow-covered ground merges with a white overcast, creating a condition in which ground textural cues are absent and the horizon is indistinguishable. Although visibility may be unrestricted in the atmospheric whiteout, there is essentially nothing to see except the runway or runway markers; an approach made in this condition must therefore be accomplished with a close eye on the altitude and attitude instruments to prevent spatial disorientation and inadvertent ground contact. In the blowing-snow whiteout, visibility is restricted drastically by snowflakes, and often those snowflakes have been driven into the air by the propeller or rotor wash of the affected aircraft. Helicopter landings on snow-covered ground are particularly likely to create blowing-snow whiteout. Typically, the helicopter pilot tries to maintain visual contact with the ground during the sudden rotor-induced whiteout, gets into an unrecognized drift to one side, and shortly thereafter contacts the ground with sufficient lateral motion to cause the craft to roll over. Pilots flying where whiteouts can occur must be made aware of the hazards of whiteout approaches, as the disorientation induced usually occurs unexpectedly under visual rather than instrument meteorologic conditions.

One puzzling illusion that occurs when visual orientation cues are minimal is visual autokinesis (Fig. 7).[1] A small, dim light seen against a dark background is an ideal stimulus for producing autokinesis. After 6 to 12 s of visually fixating the light, one can observe it to move at anywhere between 0.2 and 20 degrees/s, in one particular direction or in several directions in succession. Peripheral visual autokinesis is associated with smooth apparent movements and large apparent displacements, while central visual autokinesis is often saccadic or jerky, and results in little apparent displacement of the object fixated. In general, the larger the object and the brighter the object the less the autokinetic effect. The shape of the object seems to have little effect on the magnitude of the illusion, however. Nor does providing a larger number of objects necessarily reduce the illusory effect, as multiple objects can appear to move, either as a unit or independently, as vigorously as one alone. The physiologic mechanism of visual autokinesis is not understood; in fact, it is not even established with certainty whether actual eye movements are associated with autokinesis. One suggested explanation for the autokinetic phenomenon is that the eyes tend to drift involuntarily, perhaps because of inadequate or inappropriate vestibular stabilization, and checking the drift requires efferent oculomotor activity having sensory correlates that create the illusion.

Whatever the mechanism, the effect of visual autokinesis on pilots is of great importance. Anecdotes abound of pilots who fixate a star or a stationary ground light at night, and seeing it move because of autokinesis, mistake it for another aircraft and try to intercept or join up with it. Another untoward effect of the illusion occurs when a pilot flying at night perceives a relatively stable aircraft--one which he must intercept or follow--to be moving erratically, when in fact it is not; the unnecessary and undesirable control inputs the pilot makes to compensate for the illusory movement of the target aircraft represent increased work and wasted motion at best, and an operational hazard at worst.

To help avoid or reduce the autokinetic illusion, one should try to maintain a well-structured visual environment in which spatial orientation is unambiguous. Since this is rarely possible in night flying, it has been suggested that: (1) the gaze should be shifted frequently to avoid prolonged fixation of a target light; (2) the target should be viewed beside or through, and in reference to, a relatively stationary structure such as a canopy bow; (3) one should make eye, head, and body movements to try to destroy the illusion; and (4) as always, one should monitor the flight instruments to help prevent or resolve any perceptual conflict. Equipping aircraft with more than one light or with luminescent strips to enhance recognition at night has probably helped reduce problems with autokinesis. It has not abolished them, however.

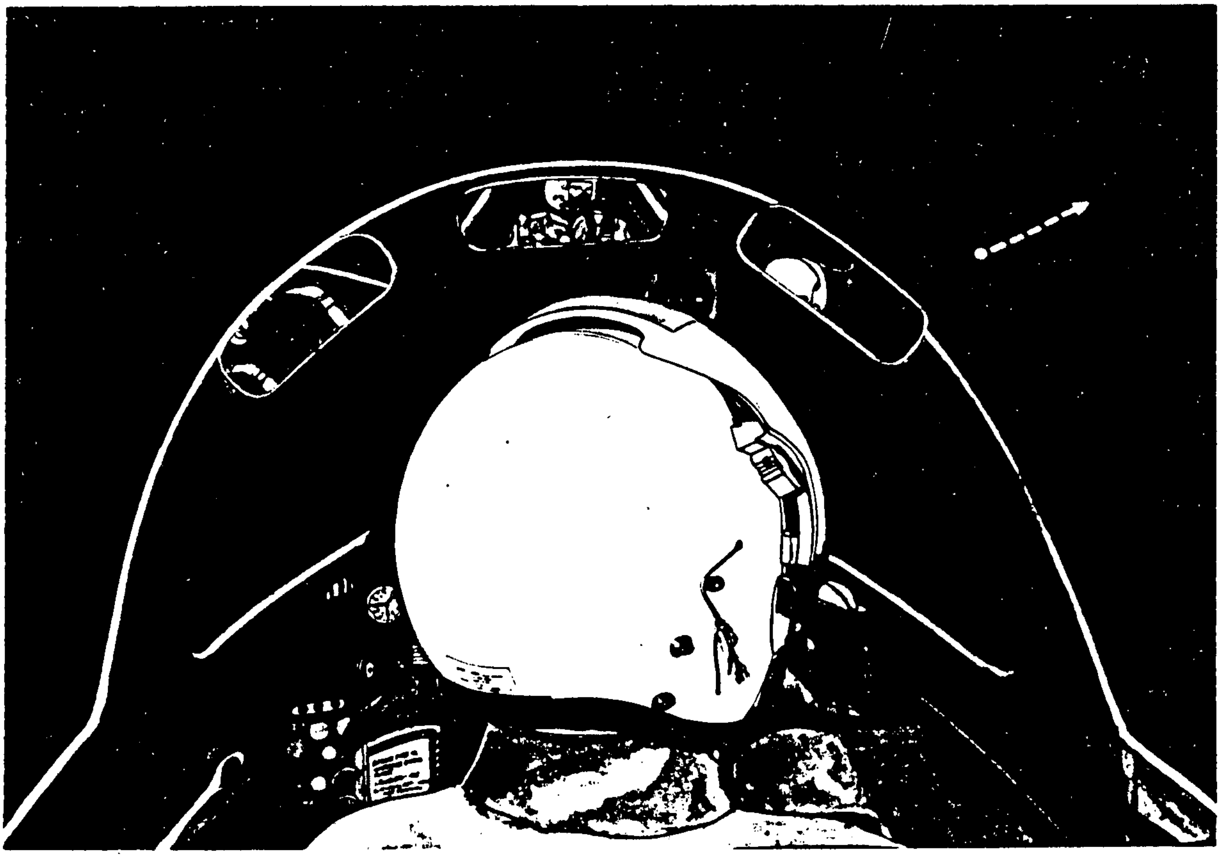


Figure 7. Visual autokinesis. A small, solitary light or small group of lights seen in the dark can appear to move, when in fact they are stationary.

So far we have discussed visual illusions created by excessive orientation-processing demands being placed on focal vision when adequate orientation cues are not available through ambient vision, or by strong but false orientation cues being received through focal vision. But ambient vision can itself be responsible for creating orientational illusions whenever orientation cues received in the visual periphery are misleading or misinterpreted. Probably the most compelling of such illusions are the vection illusions.[3] Vection is the visually induced perception of motion of the self in the spatial environment (self-motion), and can be a sensation of linear motion (linear vection) or angular motion (angular vection).

Nearly everyone who drives an automobile has experienced one very common linear vection illusion: when a driver is waiting in his car at a stop light and a presumably stationary bus or truck in the adjacent lane creeps forward, a compelling illusion that his own car is creeping backward can result (prompting a swift but surprisingly ineffectual stomp on the brake). Another example is that of a passenger sitting in a stationary train when the train on the adjacent track begins to move: he can experience the strong sensation that his own train is moving in the opposite direction (Fig. 8a). Linear vection is one of the factors that make close formation flying so difficult, as the pilot can never be sure whether his own aircraft or that of his lead or wingman is responsible for the relative motion of his aircraft.

Angular vection occurs when peripheral visual cues convey the information that one is rotating; and the perceived rotation can be in pitch, roll, yaw, or any other plane. Although angular vection illusions are not common in everyday life, they can be generated readily in a laboratory by enclosing a stationary subject in a rotating striped drum. Usually within 10 s after the visual motion begins, the subject perceives that he, rather than the striped drum, is rotating. A pilot can experience angular vection if the rotating anticollision light on his aircraft is left on during flight through clouds or fog: the revolving reflection provides a strong ambient visual stimulus signalling rotation in the yaw plane. Another condition resulting in angular vection is that in which a just-activated landing light rotates forward under the wing or nose, casting an upward-moving area of illumination in the surrounding fog or cloud, possibly even creating a rising false horizon. As a result of the illusory pitch vection generated, the pilot could be tempted to raise the nose of the aircraft at a most inappropriate time.

Fortunately, the vection illusions are not all bad. The most advanced flight simulators depend on linear and angular vection to create the illusion of flight (Fig. 8b). When the visual flight environment is dynamically portrayed in wide-field-of-view flight simulators, the illusion of actual flight is so complete and compelling that additional mechanical motion is rendered superfluous.

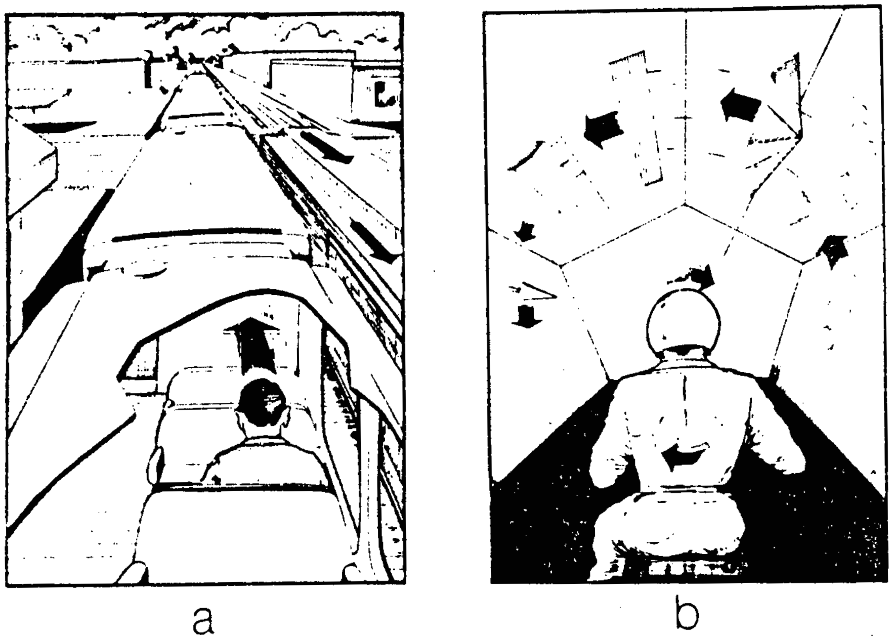


Figure 8. Vection illusions. a. Linear vection. In this example, adjacent vehicle seen moving aft in subject's peripheral vision causes him to feel he is moving forward. b. Angular vection. Visually perceived objects revolving around subject in flight simulator cause him to sense self-rotation in opposite direction --in this case a rolling motion to the right.

Another result of false ambient visual orientational cueing is the lean-on-the-sun illusion. On the ground, we are accustomed to seeing the brighter visual surround above and the darker below, regardless of the position of the sun. The direction of this gradient in light intensity thus helps us orient with respect to the surface of the earth. In cloud, however, such a gradient usually does not exist; and when it does, the lighter direction is generally toward the sun and the darker away from it. But the sun is almost never directly overhead; as a consequence, a pilot flying in a thin cloud layer tends to perceive falsely the direction of the sun as directly overhead, and to align his aircraft accordingly. This misperception causes him to bank in the direction of the sun--whence the name of the illusion. A variant of this phenomenon involves a somewhat different mechanism: sometimes a pilot remembers the relative bearing of the sun when he first penetrated the weather, and he unconsciously tries to keep the sun in the same relative position whenever it peeks through the cloud. On a prolonged flight in intermittent weather, the changing position of the sun in the sky can cause the pilot to become mildly confused and fly his aircraft with less precision than he would in either continuously visual or continuously instrument meteorologic conditions.

Often the horizon perceived through ambient vision is not really horizontal. Quite naturally, this misperception of the horizontal creates hazards to flight. A sloping cloud deck, for example, is very difficult to perceive as anything but horizontal if it extends for any great distance in the pilot's peripheral vision (Fig. 9). Uniformly sloping terrain can also create an illusion of horizontality, with disastrous consequences for the pilot thus deceived. Many aircraft have crashed as a result of the pilot's entering a canyon with an apparently level floor that actually rises faster than the airplane can climb; the pilot arrives at the end of the canyon "out of altitude, airspeed, and ideas," as they say. Sometimes a distant rain shower can obscure the real horizon and create the impression of a horizon at the proximal edge (base) of the rainfall. If the shower is seen just beyond the runway during an approach to landing, the pilot can misjudge the pitch attitude of his aircraft and make inappropriate pitch corrections on the approach.

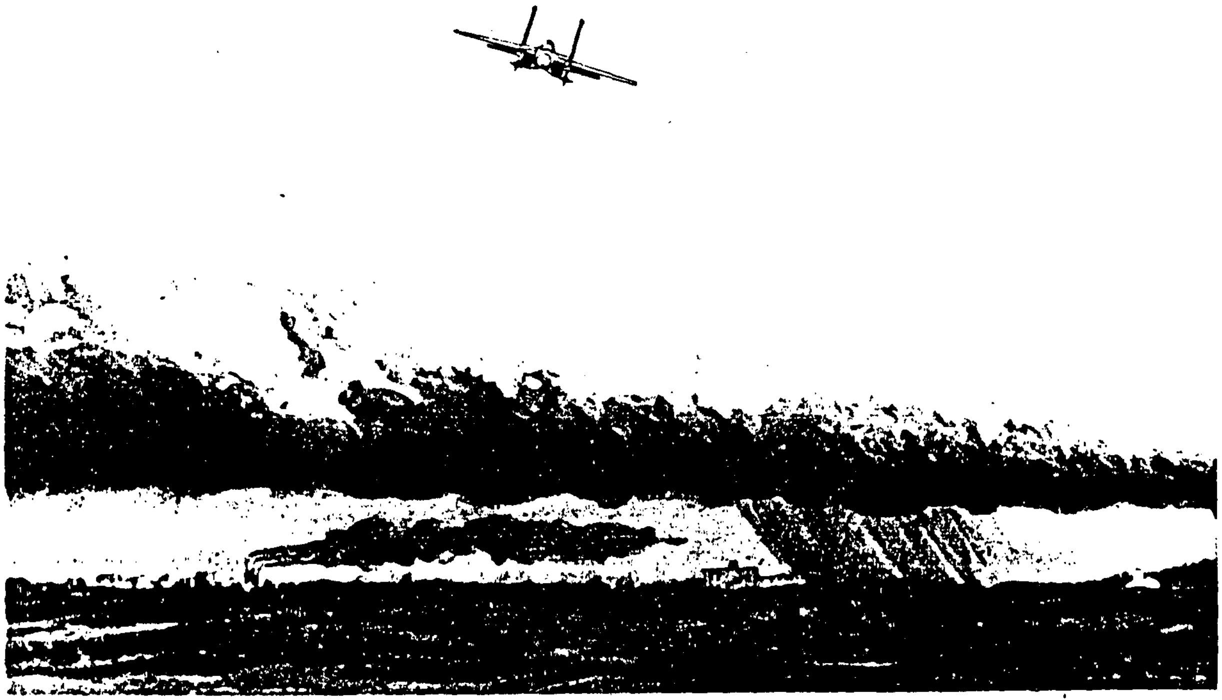


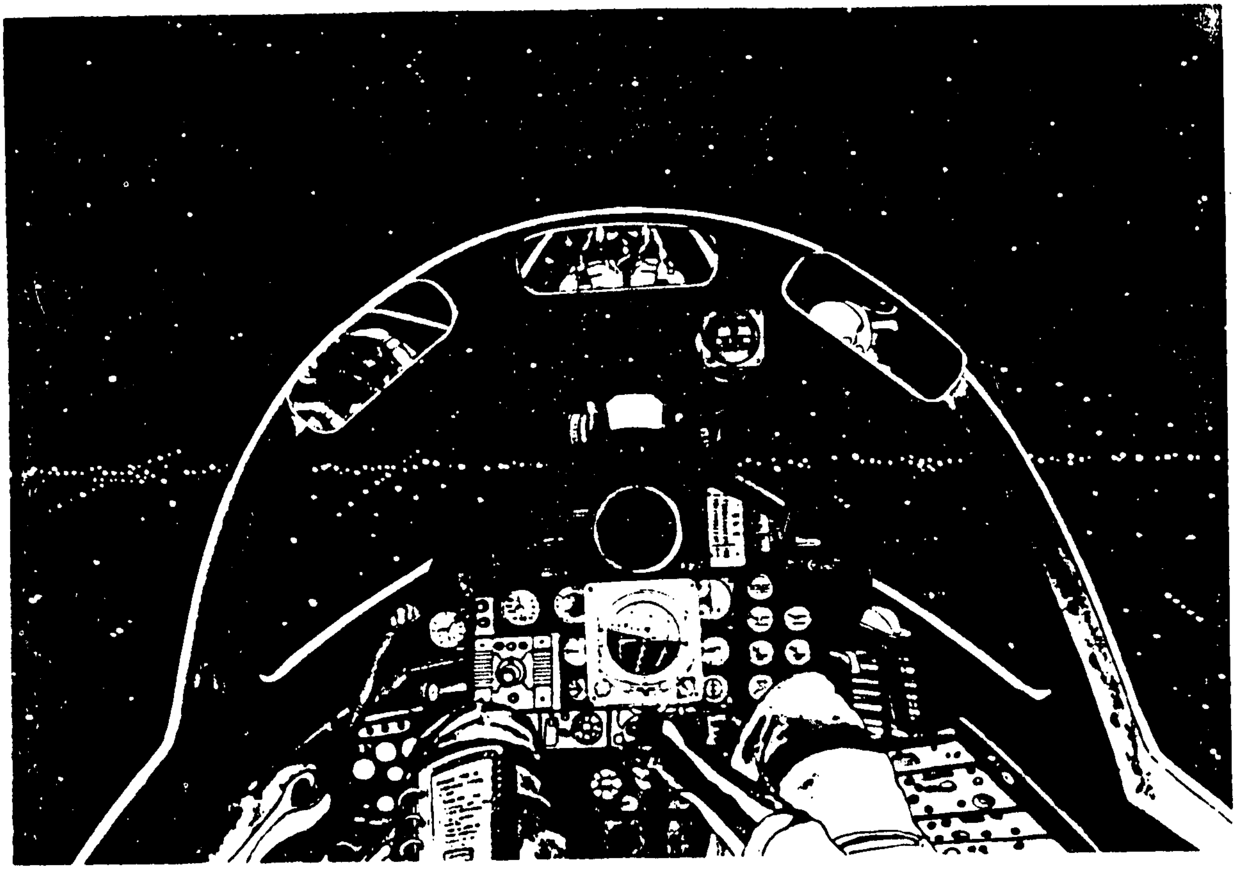
Figure 9. A sloping cloud deck, which the pilot misperceives as a horizontal surface.

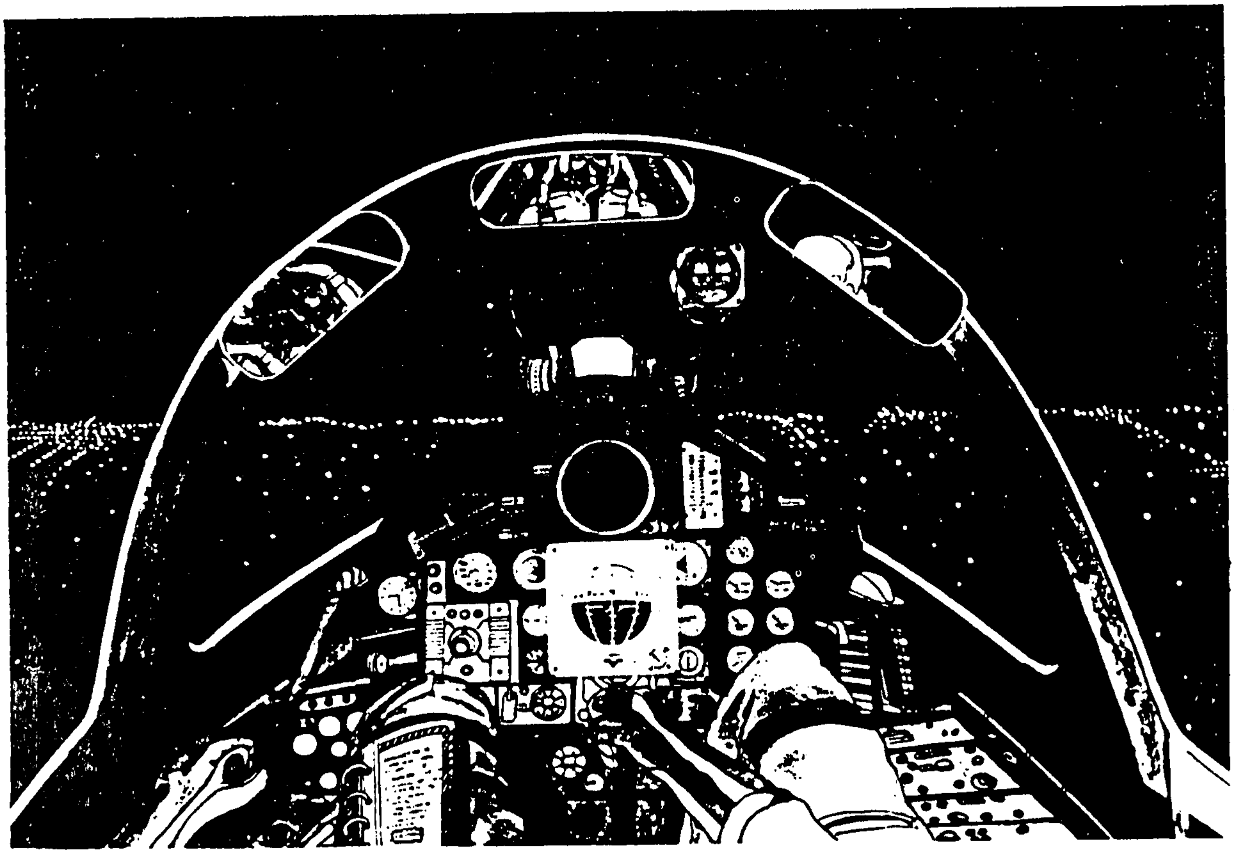
Pilots are especially susceptible to misperception of the horizontal while flying at night (Fig. 10). Isolated ground lights can appear to the pilot to be stars, causing him to think he is in a nose-high or one-wing-low attitude. Correcting for such a false impression can, of course, be fatal. Frequently no stars are visible because of an overcast. Unlighted areas of terrain can then blend with the dark overcast to create the illusion that the unlighted terrain is part of the sky. One extremely hazardous situation is that in which a takeoff is made over an ocean or other large body of water that cannot be distinguished visually from the night sky. Many pilots in this situation have perceived the shoreline receding beneath them to be the horizon and some have reacted to this false percept with disastrous consequences.

Pilots flying at very high altitudes can sometimes experience difficulties with control of aircraft attitude, because at high altitudes the horizon is lower with respect to the plane of level flight than it is at the lower altitudes where most pilots usually fly. As a reasonable approximation, the angle of depression of the horizon in degrees equals the square root of the altitude in kilometers. A pilot flying at an altitude of 15 km thus sees the horizon almost 4 degrees below the extension of his horizontal plane. If he visually orients to the view from his left cockpit window, he might be inclined to fly with the left wing 4 degrees down to level it with the horizon. If he does this, and then looks out his right window, he would see the right wing 8 degrees above the horizon, with half of that elevation due to his own erroneous control input. He might also experience problems with pitch control, as the depressed horizon can cause him to perceive falsely a 4-degree nose-high pitch attitude.

Finally, the disorienting effects of the northern lights and of aerial flares should be mentioned. Aerial refueling at night in high northern latitudes is often made quite difficult by the northern lights, which provide false cues of verticality to the pilot's peripheral vision. In addition, the movement of the auroral display may make the pilot susceptible to vection illusions. Similarly, when aerial flares are dropped, they may

Figure 10. Misperception of the horizontal at night. Above: Ground lights appearing to be stars cause earth and sky to blend and a false horizon to be perceived. Below: Blending of overcast sky with unlighted terrain or water causes horizon to appear lower than is actually the case.





descend vertically--or they may drift with the wind, creating false cues of verticality. Their motion may also create vection illusions. An important additional factor is that the aurora and aerial flares can be so bright as to reduce the apparent intensity, and therefore the orientational cueing strength, of the aircraft instrument displays.

Vestibular Illusions. The vestibulocerebellar axis processes orientation information from the vestibular end-organs, the nonvestibular proprioceptors, and the peripheral visual fields. In the absence of adequate ambient visual orientation cues, the inadequacies of the vestibular and other orienting senses can, and generally do, result in orientational illusions. It is convenient and conventional to discuss the vestibular illusions in relation to the two labyrinthine components that generate them--the semicircular ducts and the otolith organs.

The somatogyral illusion results from the inability of the semicircular ducts to register accurately a prolonged rotation, i.e., sustained angular velocity. When a person is subjected to an angular acceleration about the yaw axis, for example, the angular motion is at first perceived accurately, because the dynamics of the cupula-endolymph system cause it to respond as an integrating angular accelerometer (i.e., as a rotation rate sensor) at stimulus frequencies in the physiologic range (Fig. 11). If the acceleration is followed immediately by a deceleration, as usually happens in the terrestrial environment, the total sensation of turning one way and then stopping the turn is quite accurate (Fig. 12). But if the angular acceleration is not followed by a deceleration, and a constant angular velocity results instead, the sensation of rotation becomes less and less and eventually disappears as the cupula gradually returns to its resting position in the absence of an angular acceleratory stimulus (Figs. 12, 13). If the rotating subject is subsequently subjected to an angular deceleration after a period of prolonged constant angular velocity--say, after 10 s or more of constant-rate turning--his cupula-endolymph system then signals a turn in the direction opposite that of the prolonged constant angular velocity, even though he is really only turning less rapidly in the same direction. This sensory response occurs because the angular momentum of the rotating endolymph causes it to press against the cupula, forcing the cupula to deviate in the direction of endolymph flow, which is the same direction the cupula would deviate if the subject were to accelerate in the direction opposite his initial acceleration. Even after rotation actually ceases, the sensation of rotation in the direction opposite that of the sustained angular velocity persists for several seconds--half a minute or longer with a large decelerating rotational impulse. Technically speaking, a somatogyral illusion is the sensation of turning in the opposite direction that occurs whenever one undergoes angular deceleration from a condition of constant angular velocity. It is practical, however, to include in this category of illusions the sensation of turning more slowly and eventually ceasing to turn while angular velocity persists, because the two illusions have a common underlying mechanism and they inevitably occur in pairs. An even broader definition of somatogyral illusion is "any discrepancy between actual and perceived rate of self-rotation that results from an abnormal angular acceleratory stimulus pattern." The term "abnormal" in this case implies the application of low-frequency stimuli, outside the useful portion of the transfer characteristics of the semicircular duct system.

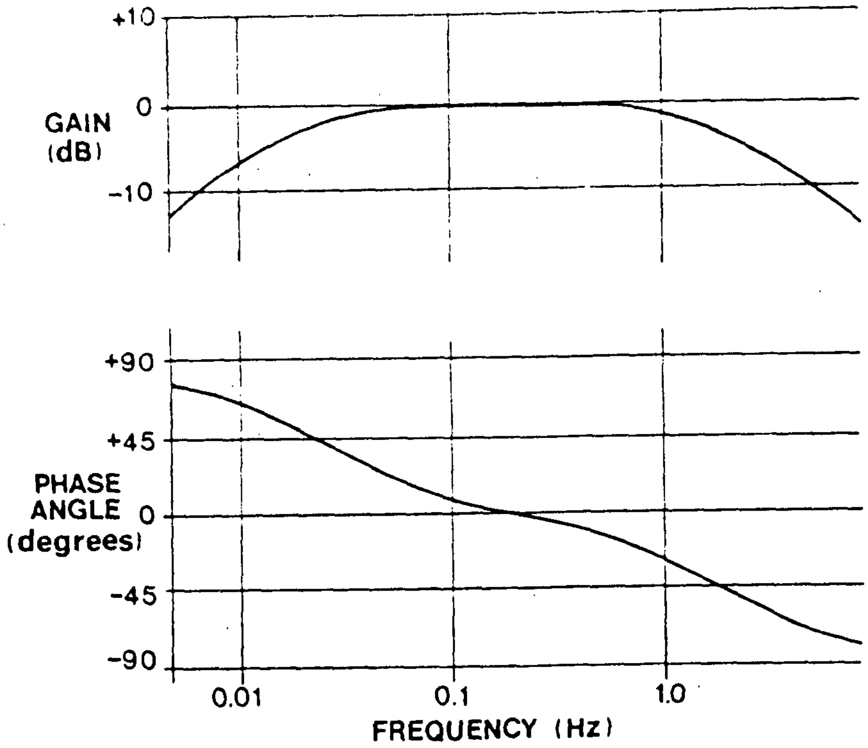


Figure 11. Transfer characteristics of the semicircular duct system as a function of sinusoidal stimulus frequency. Gain is the ratio of the magnitude of peak perceived angular velocity to peak delivered angular velocity; phase angle is a measure of the amount of advance or delay between peak perceived and peak delivered angular velocity. Note that in the physiologic frequency range (roughly 0.05 to 1 Hz), perception is accurate; i.e., gain is close to unity (0 dB) and phase shift is minimal. At lower stimulus frequencies, however, the gain drops off rapidly and the phase shift approaches 90 degrees, which means that angular velocity becomes difficult to detect and that angular acceleration is perceived as velocity. (Adapted from Peters.)[4]

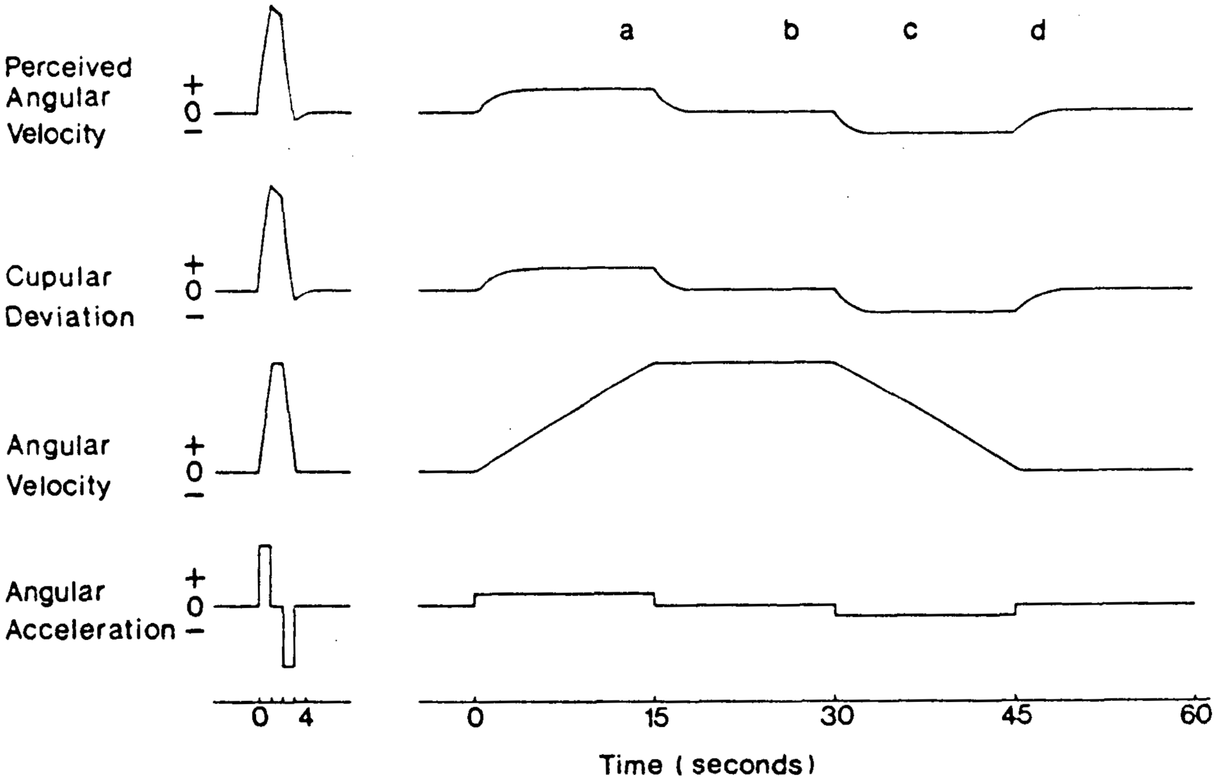


Figure 12. Effect of stimulus pattern on perception of angular velocity. On the left, the high-frequency character of the applied angular acceleration results in a cupular deviation that is nearly proportional, and perceived angular velocity that is nearly identical, to the angular velocity developed. On the right, the peak angular velocity developed is the same as that on the left, but the low-frequency character of the applied acceleration results in cupular deviation and perceived angular velocity that appear more like the applied acceleration than the resulting velocity. This causes one to perceive: (a) less than the full amount of the angular velocity, (b) that he is not turning when he actually is, (c) a turn in the opposite direction from that of the actual turn, (d) that turning persists after it has actually stopped. These false perceptions are somatogyral illusions.

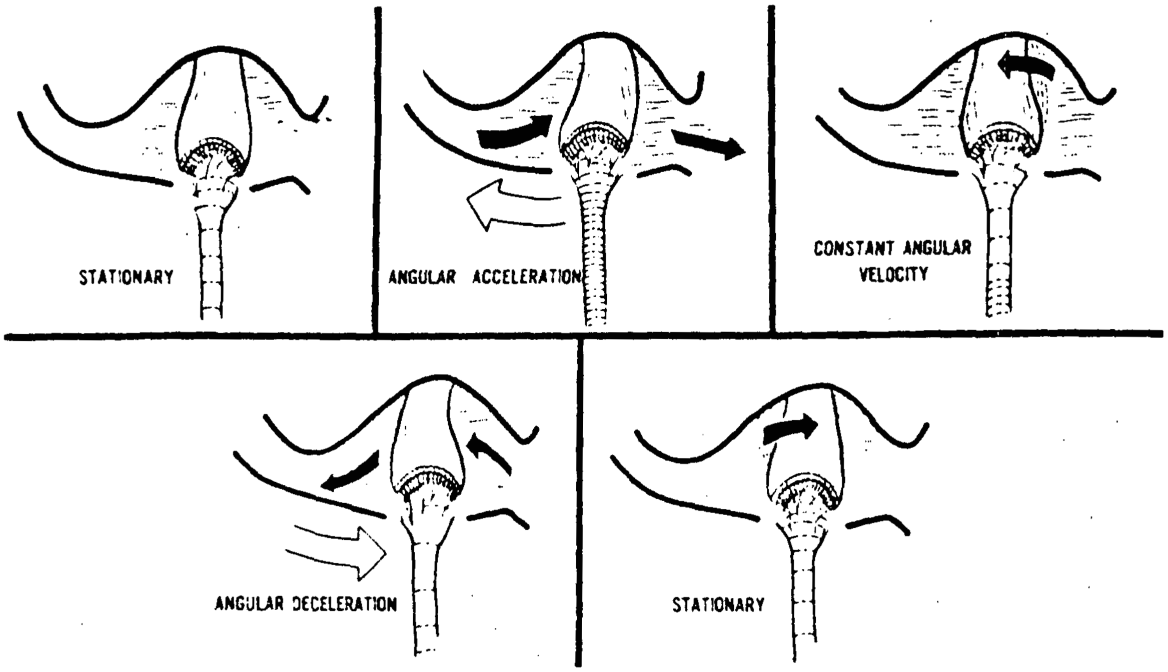
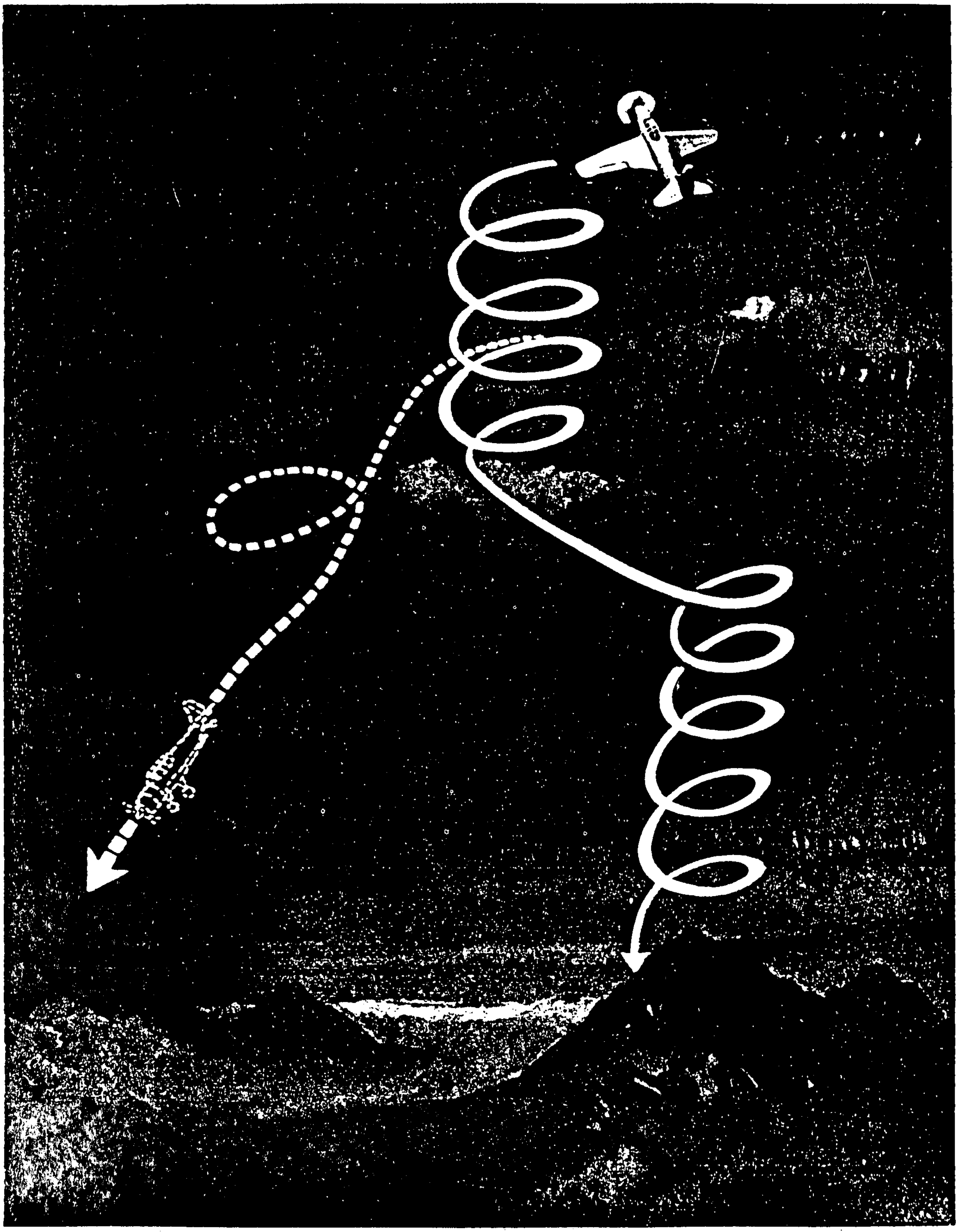


Figure 13. Pictorial representation of mechanical events occurring in a semicircular duct and resulting action potentials in associated ampullary nerve during somatogyral illusions. Angular acceleration pattern applied is shown in right side of Figure 12.

In flight under conditions of reduced visibility (night or instrument weather), somatogyral illusions can be deadly. The *graveyard spin* is the classic example of how somatogyral illusions can disorient a pilot, with fatal results. This situation begins with the pilot intentionally or unintentionally entering a spin, let's say to the left (Fig. 14). At first the pilot perceives the spin correctly, as the angular acceleration associated with entering the spin deviates the appropriate cupulae the appropriate amount in the appropriate direction. The longer the spin persists, however, the more the sensation of spinning to the left diminishes as the cupulae return to their resting positions. If the pilot tries to stop the spin to the left by applying right rudder, the angular deceleration causes him to perceive a spin to the right, even though the only real result of his action is termination of the spin to the left. A pilot who is ignorant of the possibility of such an illusion is then likely to make counterproductive left rudder inputs to negate the unwanted erroneous sensation of spinning to the right. These inputs keep the airplane spinning to the left, which gives the pilot the desired sensation of not spinning but does not bring the airplane under control. To extricate himself from this very hazardous situation the pilot must read the aircraft flight instruments and apply control inputs to make the instruments give the desired readings (push right rudder to center the turn needle, in this example). Unfortunately, this may not be so easy to do. The angular accelerations created by both the multiple-turn spin and the pilot's spin-recovery attempts can elicit strong but inappropriate vestibulo-ocular reflexes, including nystagmus. In the usual terrestrial environment these reflexes help stabilize the retinal image of the visual surround; but in this situation they only destabilize it, because the visual surround (cockpit) is already fixed with respect to the pilot. Reading the flight instruments thus becomes difficult or impossible in this situation, and the pilot is left with only his false sensations of rotation to rely on for spatial orientation and aircraft control.[5]

While the lore of early aviation provided the graveyard spin as an illustration of the hazardous nature of somatogyral illusions, a much more common example occurring all too often in present-day aviation is the graveyard spiral (Fig. 15). In this situation the pilot has intentionally or unintentionally gotten himself into a prolonged turn with a moderate amount of bank. After a number of seconds in the turn the pilot loses the sensation of turning because his cupula-endolymph system cannot respond to constant angular velocity. The percept of being in a bank as a result of the initial roll into the banked attitude also decays with time, because the net gravitoinertial force vector points toward the floor of the aircraft during coordinated flight (whether the aircraft is in a banked turn or flying straight and level) and the otolith organs and other graviceptors normally signal that down is in the direction of the net sustained gravitoinertial force. As a result, when the pilot tries to stop the turn by rolling back to a wings-level attitude, he not only feels he is turning in the direction opposite that of his original turn, but he also feels he is banked in the direction opposite that of his original bank. Unwilling to accept this sensation of making the wrong control input, the hapless pilot rolls back into his original banked turn. Now his sensation is compatible with his desired mode of flight, but his instruments say he is losing altitude (because the banked turn is wasting lift) and still turning. So he pulls back on the stick and perhaps adds power to arrest the unwanted descent and regain the lost altitude. This action would be successful if the aircraft were flying wings-level, but with the aircraft in a banked attitude it tightens the turn, serving only to make matters worse. Unless the pilot eventually recognizes his error

Figure 14. The graveyard spin. After several turns of a spin the pilot begins to lose the sensation of spinning. Then when he tries to stop the spin, the resulting somatogyral illusion of spinning in the opposite direction makes him reenter the original spin. (Solid line indicates actual motion; dotted line indicates perceived motion.)



and rolls out of his unperceived banked turn, he will continue to descend in an ever-tightening spiral toward the ground--whence the name, graveyard spiral.

Whereas a somatogyral illusion is a false sensation, or lack of sensation, of self-rotation in a subject undergoing unusual angular motion, an *oculogyral illusion* is a false sensation of motion of an object viewed by such a subject.[6] For example: if a vehicle with a subject inside is rotating about a vertical axis at a constant velocity and suddenly stops rotating, the subject experiences not only a somatogyral illusion of himself rotating in the opposite direction, but also an oculogyral illusion of an object in front of him moving in the opposite direction. Thus, a somewhat oversimplified definition of the oculogyral illusion is that it is the visual correlate of the somatogyral illusion; but its very low threshold and its lack of total correspondence with presumed cupular deviation suggest a more complex mechanism. The attempt to maintain visual fixation during a vestibulo-ocular reflex elicited by angular acceleration is probably at least partially responsible for the oculogyral illusion. (A similar mechanism underlies the illusory movement of the moon when one tries to fixate it visually while the relative movement of surrounding clouds is eliciting an optokinetic tracking reflex.) In an aircraft during flight at night or in weather an oculogyral illusion generally confirms a somatogyral illusion: the pilot who falsely perceives that he is turning in a particular direction also observes his instrument panel to be moving in the same direction.

The vestibular Coriolis effect, Coriolis cross-coupling effect, vestibular cross-coupling effect, or simply the *Coriolis illusion*, is another false percept that can result from unusual stimulation of the semicircular duct system. To illustrate this phenomenon, let us consider a subject who has been rotating in the plane of his horizontal semicircular ducts (roughly the yaw plane) long enough for the endolymph in those ducts to attain the same angular velocity as his head: the cupulae in the ampullae of his horizontal ducts have returned to their resting positions, and the sensation of rotation has ceased (Fig. 16a). If the subject then nods his head forward in the pitch plane, let's say a full 90 degrees for the sake of simplicity, he is

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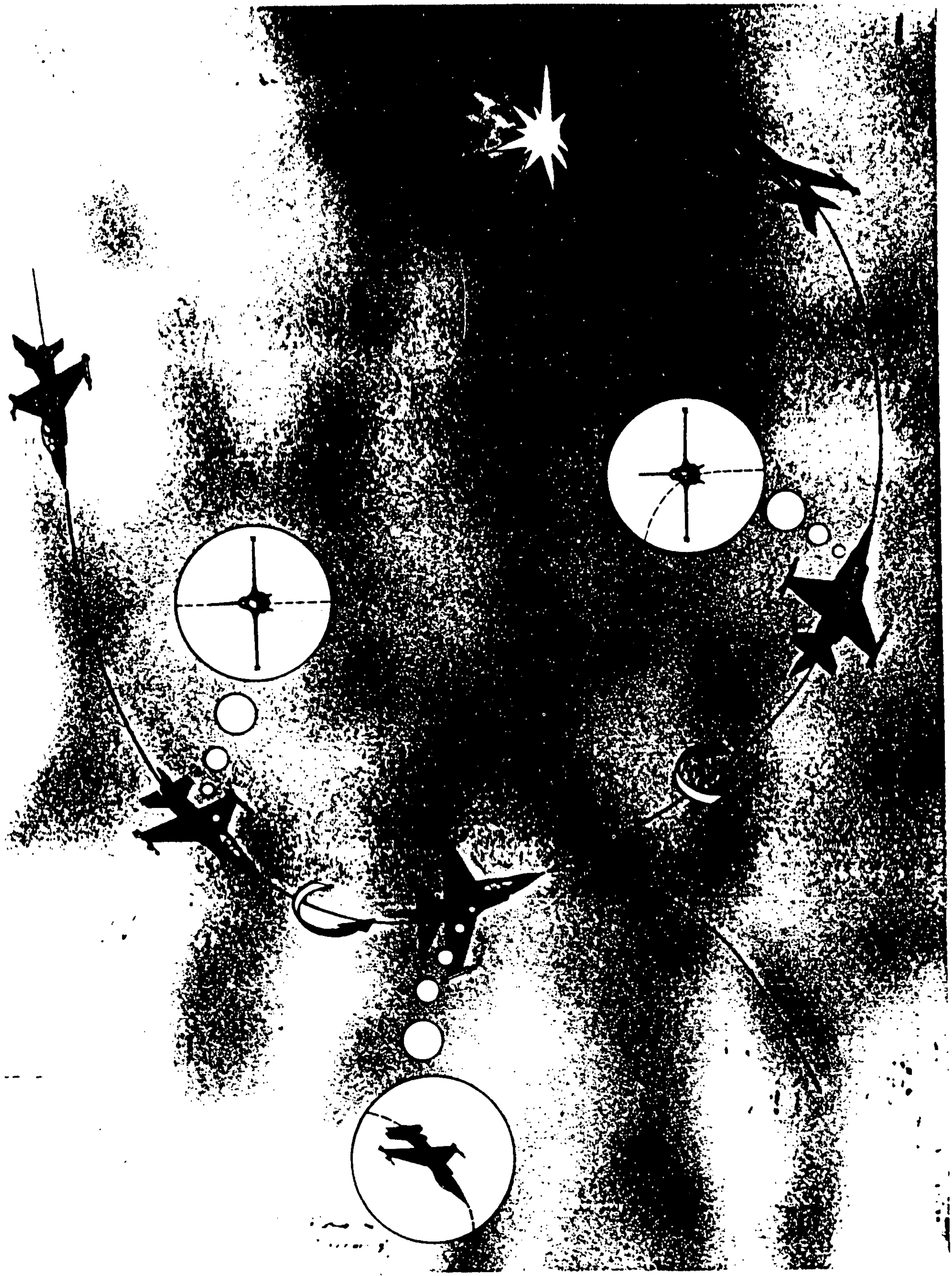
Figure 15. The graveyard spiral. The pilot in a banked turn loses the sensation of being banked and turning. Upon trying to reestablish a wings-level attitude and stop the turn, he perceives that he is banked and turning in the opposite direction from his original banked turn; i.e., he experiences a somatogyral illusion. Unable to tolerate the sensation that he is making an inappropriate control input, the pilot banks back into the original turn.



completely removing his horizontal semicircular ducts from the plane of rotation and inserting his two sets of vertical semicircular ducts into the plane of rotation (Fig. 16b). While the angular momentum of the subject's rotating head is forcibly transferred at once out of the old plane of rotation relative to his head, the angular momentum of the endolymph in the horizontal duct is dissipated more gradually. The torque resulting from the continuing rotation of the endolymph causes the cupulae in the horizontal ducts to be deviated, and a sensation of angular motion occurs in the new plane of the horizontal ducts--now the roll plane relative to the subject's body. Simultaneously, the endolymph in the two sets of vertical semicircular ducts must acquire angular momentum, as these ducts have been brought into the plane of constant rotation. The torque required to impart this change in momentum causes deflection of the cupulae in the ampullae of these ducts, and a sensation of angular motion in this plane--the yaw plane relative to the subject's body--is the result. The combined effect of the cupular deflection in all three sets of semicircular ducts is that of a suddenly imposed angular velocity in a plane in which no actual angular acceleration relative to the subject has occurred. In the example given, if the original constant-velocity yaw is to the right and the subject pitches his head forward, the resulting Coriolis illusion experienced is that he and his immediate surroundings are suddenly rolling to the right and yawing to the right.

A particular perceptual phenomenon experienced occasionally by pilots of relatively high-performance aircraft during instrument flight has been attributed to the Coriolis illusion because it occurs in conjunction with large movements of the head under conditions of prolonged constant angular velocity. It consists of a very convincing sensation of rolling and/or pitching that appears suddenly after the pilot diverts his attention from the instruments in front of him and moves his head to view some switches or displays elsewhere in the cockpit. This illusion is especially deadly because it is most likely to occur during an instrument approach, a phase of flight in which altitude is being lost rapidly and cockpit chores (e.g., radio frequency changes) repeatedly require the pilot to break up his instrument cross-check. Whether the sustained angular velocities associated with instrument flying are sufficient to create Coriolis illusions of any great magnitude is debatable, however[7]; and another mechanism (the G-excess effect) has been proposed to explain the illusory rotations experienced with head movements in flight. Even if not responsible for spatial disorientation in flight, the Coriolis illusion is useful as a tool to demonstrate the fallibility of our nonvisual orientation senses. Nearly every military pilot living today has experienced the Coriolis illusion in the Barany chair or some other rotating device as part of his physiological training; and for most of them it was then that they first realized their own orientation senses really cannot ~~be~~ trusted--the most important lesson of all for instrument flying.

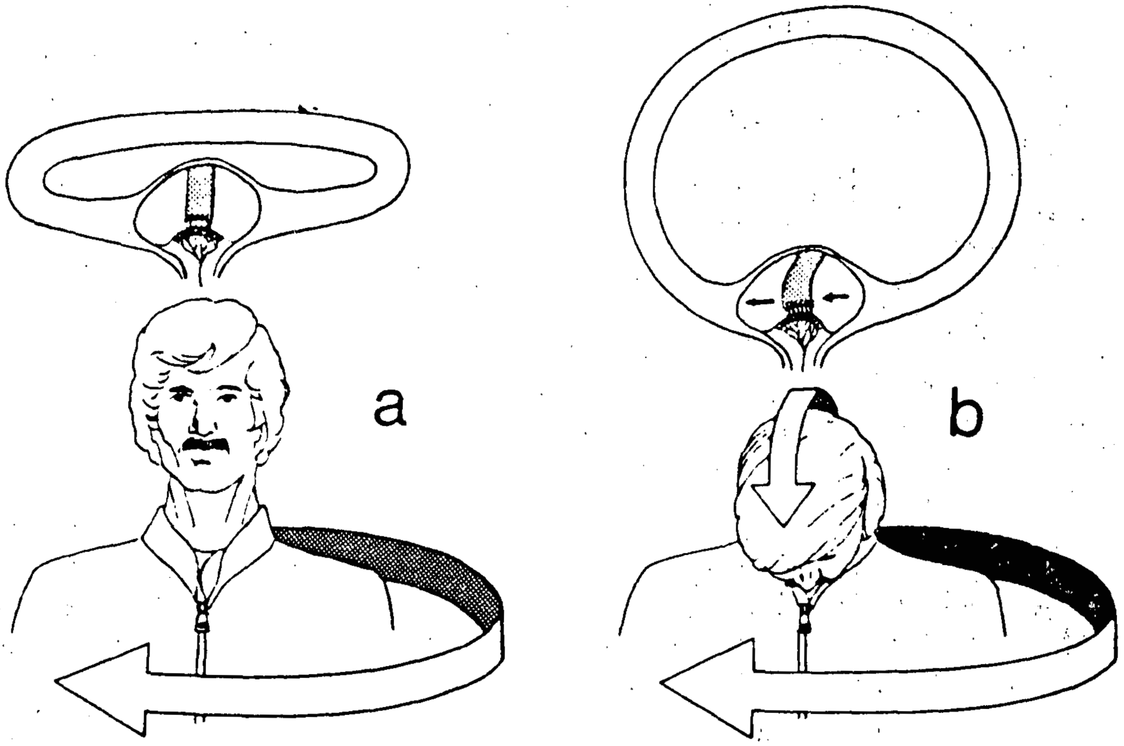


Figure 16. Mechanism of the Coriolis illusion. Subject rotating in yaw plane long enough for endolymph to stabilize in semicircular duct (a), pitches head forward (b). Angular momentum of endolymph deviates cupula, causing subject to perceive rotation in new plane of semicircular duct, even though no actual rotation occurred in that plane.

The otolith organs are responsible for a set of illusions known as somatogravic illusions. The mechanism of illusions of this type involves the displacement of otolithic membranes on their maculae by inertial forces in such a way as to signal a false orientation when the resultant gravitoinertial force is perceived as gravitational (and therefore vertical). The paragon of somatogravic illusions, the illusion of pitching up after taking off into conditions of reduced visibility, is perhaps the best illustration of this mechanism. Consider the pilot of a high-performance aircraft holding his position at the end of the runway waiting to take off. Here the only force acting on his otolithic membranes is the force of gravity, and the positions of those membranes on their maculae signal accurately that down is toward the floor of the aircraft. Suppose the aircraft now accelerates down the runway, rotates, takes off, cleans up gear and flaps, and maintains a forward acceleration of 1 G until reaching desired climb speed. The 1 G of inertial force resulting from the forward acceleration displaces the otolithic membranes toward the back of the pilot's head. In fact, the new positions of the otolithic membranes are nearly the same as they would be if the aircraft and pilot had pitched up 45 degrees,

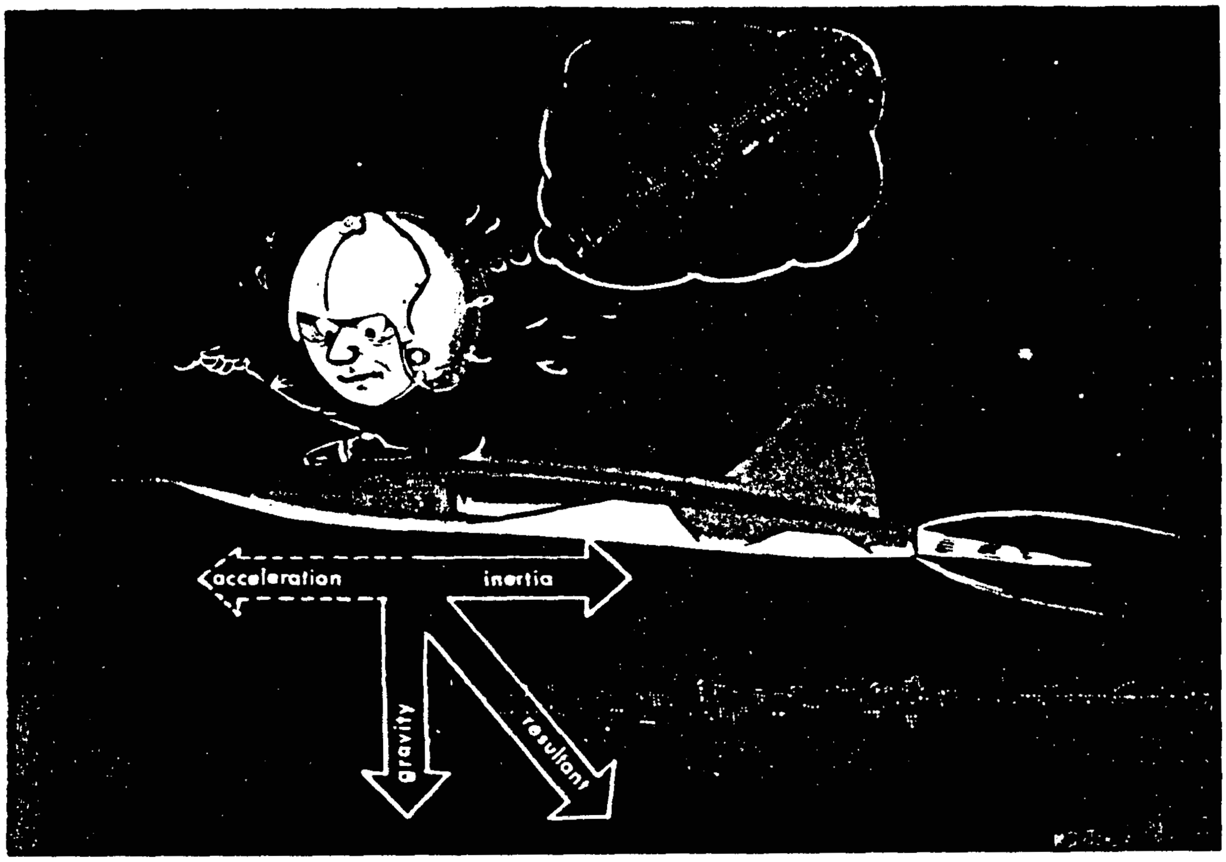


Figure 17. A somatogravic illusion occurring on takeoff. The inertial force resulting from the forward acceleration combines with the force of gravity to create a resultant gravitoinertial force directed down and aft. The pilot, perceiving down to be in the direction of the resultant gravitoinertial force, feels he is in an excessively nose-high attitude, and is tempted to push the stick forward to correct the illusory nose-high attitude.

since the new direction of the resultant gravitoinertial force vector (if we neglect the angle of attack and climb angle) is 45 degrees aft relative to the gravitational vertical (Fig. 17). Naturally, the pilot's percept of pitch attitude based on the information from his otolith organs is one of having pitched up 45 degrees; and the information from his nonvestibular proprioceptive and cutaneous mechanoreceptive senses supports this false percept, as the sense organs subserving those modalities also respond to the direction and intensity of the resultant gavitoinertial force. Given the very strong sensation of a nose-high pitch attitude, one that is not challenged effectively by the focal visual orientation cues provided by the attitude indicator, the pilot is tempted to push the nose of the aircraft down to cancel the unwanted sensation of flying nose-high. Pilots succumbing to this temptation characteristically crash in a nose-low attitude a few miles beyond the end of the runway. Sometimes, however, they are seen to descend out of the overcast nose-low and to try belatedly to pull up, as though they suddenly regained the correct orientation upon seeing the ground again. Pilots of carrier-launched aircraft need to be especially wary of the somatogravic illusion. These pilots experience pulse accelerations lasting 2 to 4 s and generating peak inertial forces of +3 to +5 G_x. Although the major acceleration is over rather quickly, the resulting illusion of nose-high pitch can persist for half a minute or more afterwards, resulting in a particularly hazardous situation for the pilot who is unaware of this phenomenon.[3]

Pilots of high-performance aircraft are not the only ones to suffer the somatogravic illusion of pitching up after takeoff. More than a dozen air transport aircraft are believed to have crashed as a result of pilots' experiencing the somatogravic illusion on takeoff.[9] A relatively slow aircraft, accelerating from 100 to 130 knots over a 10-s period just after takeoff, generates +0.16 G_x on the pilot. Although the resultant gravitoinertial force is only 1.01 G, barely perceptibly more than the force of gravity, it is directed 9 degrees aft, signifying to the unwary pilot a 9-degree nose-up pitch attitude. As many slower aircraft climb out at 6 degrees or less, a 9-degree downward pitch correction would put such an aircraft into a descent of 3 degrees or more--the same as a normal final-approach slope. In the absence of a distinct external visual horizon--even worse, in the presence of a false visual horizon (e.g., a shoreline) receding under the aircraft and reinforcing the vestibular illusion--the pilot's temptation to push the nose down can be overwhelming. This type of mishap has happened at one particular civil airport so often that a notice has been placed on navigational charts cautioning pilots flying from this airport to be aware of the potential for loss of attitude reference.

Although the classic graveyard spiral was earlier indicated to be a consequence of the pilot's suffering a somatogyral illusion, it can also be considered to result from a somatogravic illusion. A pilot who is flying "by the seat of his pants" applies the necessary control inputs to create a resultant G-force vector having the same magnitude and direction as that which his desired flight path would create. Unfortunately, any particular G vector is not unique to one particular condition of aircraft attitude and motion; and the likelihood that the G vector created by a pilot flying without reference to instruments is that of the flight condition desired is remote indeed. Specifically, once an aircraft has departed a desired wings-level attitude because of an unperceived roll, and the pilot does not correct the resulting bank, the only way he can create a G vector which matches that of the straight and level condition is with a descending spiral. In this condition, as is always the case in a coordinated turn, the centrifugal force resulting from the turn provides a G_y force which cancels the G_y component of the force of gravity that exists when the aircraft is banked. In addition, the tangential linear acceleration associated with the increasing airspeed resulting from the dive provides a $+G_x$ force which cancels the $-G_x$ component of the gravity vector that exists when the nose of the aircraft is pointed downward. Although the vector analysis of the forces involved in the graveyard spiral is somewhat complicated, a pilot can easily and automatically manipulate the stick and rudder pedals to cancel all vestibular and other nonvisual sensory indications that his aircraft is turning and diving. In one mishap involving a dark-night takeoff of a commercial airliner, the recorded flight data indicated that the resultant G force which the pilot created by his control inputs allowed him to perceive his desired 10- to 12-degree climb angle, and a net G force between 0.9 and 1.1 G, for virtually the whole flight--even though he actually levelled off and then descended in an accelerating spiral until the aircraft crashed nearly inverted (Fig. 18).

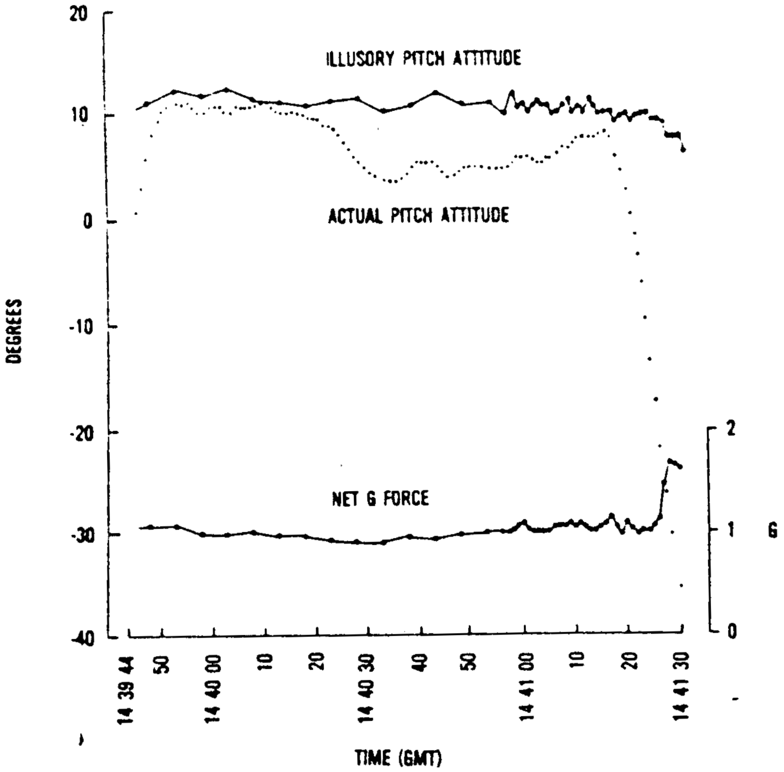


Figure 18. Flight recorder data from a wide-body jetliner that crashed less than two minutes after taking off over the ocean on a dark night. Although the net gravitoinertial force was essentially 1.0 G directed 10 to 12 degrees aft of the aircraft vertical through nearly the whole flight, the aircraft actually leveled off and eventually entered a spiral dive into the water. The fact that the desired flight profile (a straight climb) would have yielded the same gravitoinertial force environment as was actually generated is strong evidence that the pilot was spatially disoriented.

The *inversion illusion* is a type of somatogravic illusion in which the resultant gravitoinertial force vector rotates so far backward as to be pointing away from, rather than toward, the earth's surface, thus giving the subject of this phenomenon the false sensation that he is upside down. Figure 19 shows how this can happen. Typically, a steeply climbing high-performance aircraft levels off more or less abruptly at the desired altitude. This maneuver subjects the aircraft and pilot to a $-G_z$ centrifugal force resulting from the arc flown just prior to level-off. Simultaneously, as the aircraft changes to a more level attitude, airspeed picks up rapidly, adding a $+G_x$ tangential inertial force to the overall force environment. Adding the $-G_z$ centrifugal force and the $+G_x$ tangential force to the 1-G gravitational force results in a net gravitoinertial force vector that rotates backward and upward relative to the pilot. This stimulates his otolith organs in a manner similar to the way a pitch upward into an inverted position would. Even though the semicircular ducts should respond to the actual pitch downward, for some reason this conflict is resolved in favor of the otolith-organ information--perhaps because the semicircular duct response is transient while the otolith-organ response persists, or perhaps because the information from the nonvestibular proprioceptors and other mechanoreceptors reinforces that from the otolith organs. The pilot who responds to the inversion illusion by pushing forward on the stick to counter the perceived pitching up and over backward only prolongs the illusion by creating more $-G_z$ and $+G_x$ forces, thus aggravating his situation. Turbulent weather usually contributes to the development of the illusion; certainly, downdrafts are a source of $-G_z$ forces that can add to the net gravitoinertial force producing the inversion illusion. Again, one does not have to be flying a jet fighter to experience this illusion. A number of reports of the inversion illusion describe the loss of control of air transport aircraft that occurred when the pilot lowered the nose inappropriately after experiencing the illusion. *Jet upset* is the term for the sequence of events that includes instrument weather, turbulence, inability of the pilot to read his instruments, the inversion illusion, a pitch-down control input, and difficulty recovering the aircraft because of resulting aerodynamic or mechanical forces.[11]

The *G-excess illusion* can also be considered a form of somatogravic illusion, because it involves an abnormal magnitude and/or direction of applied gravitoinertial force that results in false perception of body position, and the perceptual response can be determined at lease qualitatively by a simple mechanical analysis (Fig. 20). Let us assume a subject is sitting upright in a +1-G_z environment, and he tips his head forward 30 degrees. As a result of this change in head position, his otolithic membranes slide forward the appropriate amount for a 30-degree tilt relative to vertical--say, a distance of X µm. Now suppose the same subject is sitting upright in a +2-G_z environment, and again tips his head 30 degrees forward. This time his otolithic membranes slide forward more than X µm because of the doubled gravitoinertial force acting on them. But the displacement of the otolithic membranes now corresponds not to a 30-degree forward tilt in the normal 1-G environment, but to a much greater one, theoretically as much as 90 degrees (2 sin 30 deg = sin 90 deg). The subject had initiated only a 30-degree head tilt, however, and expects to perceive no more than that. The unexpected additional perceived tilt is thus referred to the immediate environment; i.e., he perceives his vehicle, if he is in one, to have tilted by the amount equal to the difference between his actual and expected percepts of tilt. In a high-performance aircraft the G-excess illusion can occur as a result of the moderate amount of G force pulled in a turn--a penetration turn or procedure turn, for example. If the pilot has to look down and to the side to select a new radio frequency or to pick up a dropped pencil while in a turn, he should experience an uncommanded tilt in both the pitch and roll planes due to the G-excess illusion. As noted previously, the G-excess illusion may be responsible for the false sensation of pitch and/or roll generally attributed to the Coriolis illusion under such circumstances.[12]

Figure 19. The inversion illusion. Centrifugal and tangential inertial forces during a level-off combine with the force of gravity to produce a resultant gravito-inertial force that rotates backward and upward with respect to the pilot, causing him to perceive that he is suddenly upside down. Turbulent weather can produce additional inertial forces that contribute to the illusion. (Adapted from Martin and Jones.)[10]

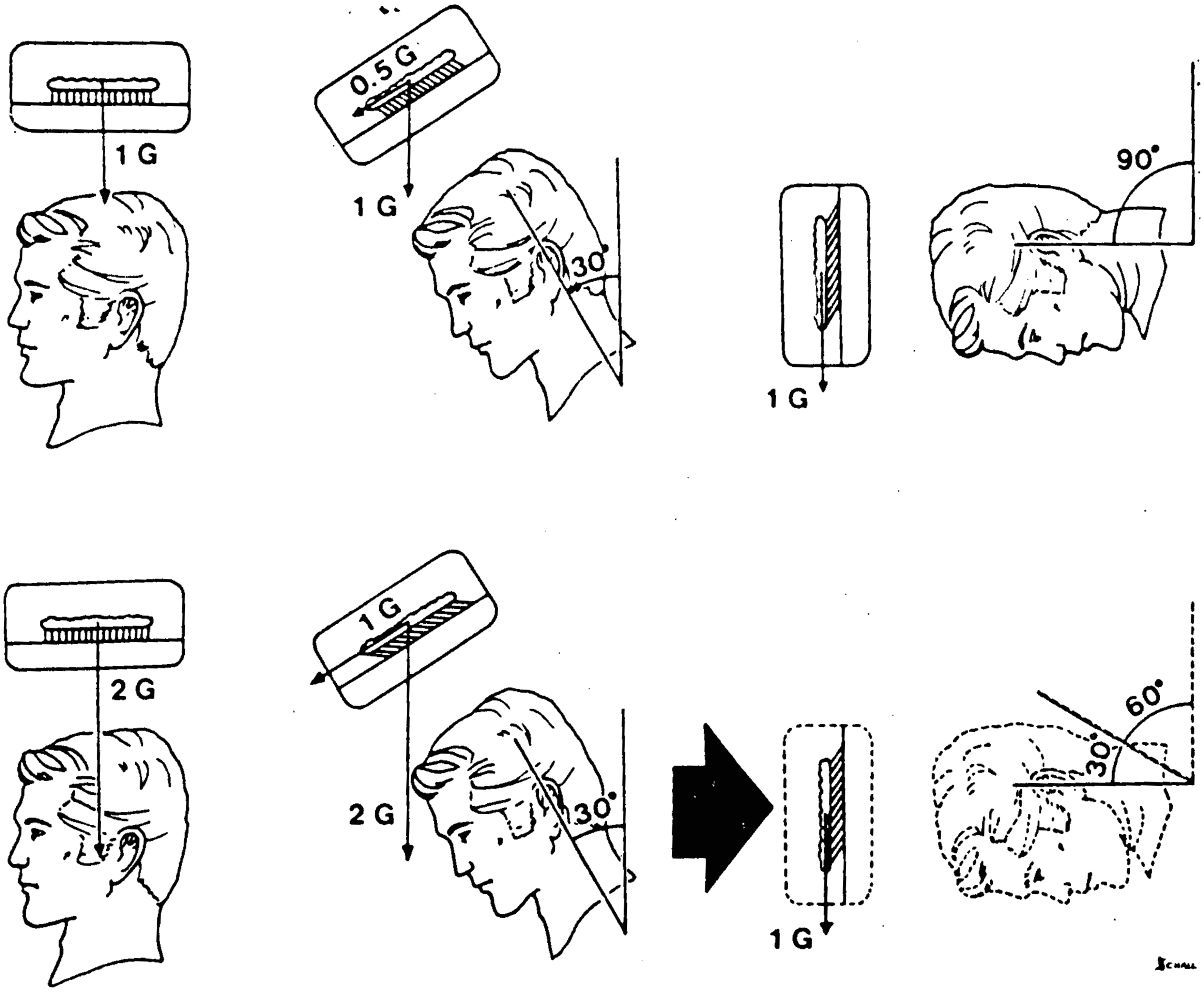


Figure 20. Mechanism of the G-excess illusion. Subject in 1-G environment (upper figures) experiences the result of a 0.5-G pull on his utricular otolithic membranes when he tilts his head 30 degrees off the vertical, and that of a 1-G pull when he tilts it a full 90 degrees. Subject in 2-G environment (lower figures) experiences the result of a 1-G pull when he tilts his head only 30 degrees. The illusory excess tilt perceived by the subject is attributed to external forces (lower right).

Another illusion of otolith-organ origin, but not classified as a somatogravic illusion because it involves a visual perceptual effect, is the oculogravic illusion. The oculogravic illusion can be thought of as a visual correlate of the somatogravic illusion, and occurs under the same stimulus conditions.[13] A pilot who is subjected to the deceleration resulting from application of speed brakes, for example, experiences a nose-down pitch because of the somatogravic illusion. Simultaneously, he observes the instrument panel in front of him to move downward, confirming his sensation of tilting forward. The oculogravic illusion is thus the visually apparent movement of an object which is actually in a fixed position relative to the subject during changing magnitude and/or direction of the net gravitoinertial force. Like the oculogyral illusion, the oculogravic illusion probably results from the attempt to maintain visual fixation during a vestibulo-ocular reflex, elicited in this case by the change in magnitude or direction of the applied G vector rather than by angular acceleration.

The elevator illusion is a special type of oculogravic illusion that results from an increase or decrease in the magnitude of the $+G_z$ force acting on a subject. When one is accelerated upward, as in an elevator, the increase in $+G_z$ force elicits a vestibulo-ocular reflex of otolith-organ origin (the elevator reflex) that drives the eyes downward. Attempting to stabilize visually the objects in a fixed position relative to the observer causes those objects to appear to shift upward when the G force is increased. The opposite effect occurs when one is accelerated downward: the reduction in the magnitude of the net gravitoinertial force to less than $+1\ G_z$ causes a reflex upward shift of the direction of gaze, and the immediate surroundings appear to shift downward. (The latter effect has also been called the oculoagravic illusion because of its occurrence during transient weightlessness.) The importance of the elevator illusion in aviation is not well documented. In one tragic mishap, however, it was probably experienced by the pilot of a military transport aircraft who became disoriented shortly after leveling off abruptly from a prolonged steady descent on a dark night over desert terrain. The transient increase in $+G_z$ force that occurred as the pilot leveled off at the landing pattern altitude most likely provoked the elevator illusion, and seeing his instrument panel rise, he compensated by pitching downward during the subsequent fatal turn to final approach. We can also assume that updrafts and downdrafts produce elevator illusions in pilots penetrating turbulent weather (Fig. 21).

By far the most common vestibular illusion in flight is the leans. Virtually every instrument-rated pilot has had it, or will get it, in one form or another at some time in his flying career. It consists of a false percept of angular displacement about the roll axis, i.e., is an illusion of bank, and is frequently associated with an attempt by the pilot to compensate for the illusion by leaning in the direction of the falsely

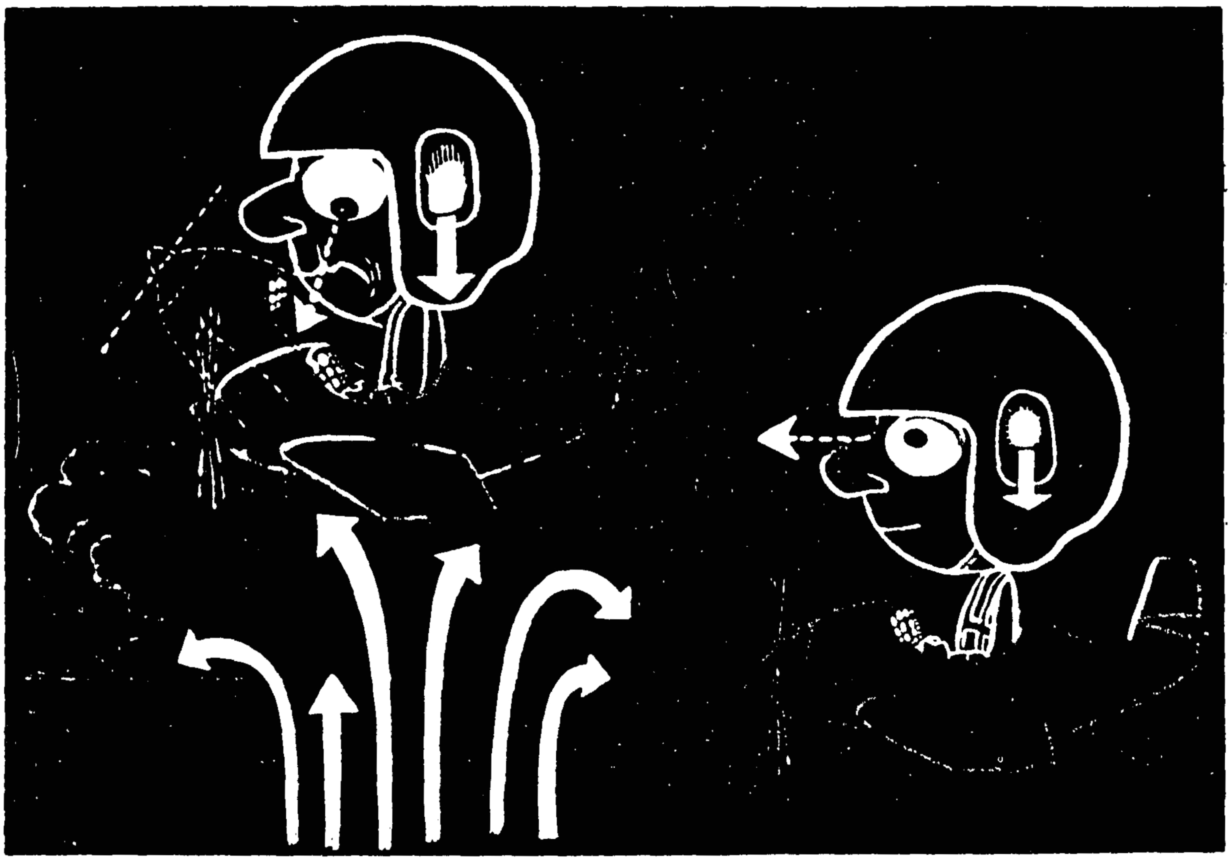


Figure 21. Elevator illusion resulting from an updraft. In this type of oculogravic illusion, the increase in $+G_z$ force elicits a vestibulo-ocular reflex of otolith-organ origin which, when visual fixation is attempted, results in a falsely perceived upward motion of the object fixated--the instrument panel in the example shown.

perceived vertical (Fig. 22). The usual explanations of the leans invoke the known deficiencies of both otolith-organ and semicircular-duct sensory mechanisms. As indicated previously, the otolith organs are not reliable sources of information about the direction of the true vertical because they respond to the resultant gravitoinertial force, not to gravity alone. Furthermore, other sensory inputs can sometimes override otolith-organ cues and result in false perception of the vertical, even when the gravitoinertial force experienced is truly vertical. The semicircular ducts can provide such false inputs in flight by responding accurately to some roll stimuli but not responding to others because they are below threshold. If, for example, a pilot is subjected to an angular acceleration in roll so that the product of the acceleration and its time of application does not reach some threshold value--say, 3 degrees/s--then he does not perceive the roll. Let us suppose this pilot, who is trying to fly straight and level, is subjected to an unrecognized and uncorrected 2-degree/s roll for 10 s: a 20-degree bank results. If the pilot suddenly notices the unwanted bank and corrects it by rolling the aircraft back upright with a suprathreshold roll rate--say, 15 degrees/s--he experiences only half of the actual roll motion that took place, the half resulting from the correcting roll. As he started perceptually from a wings-level position, he is left with the illusion of having rolled into a 20-degree bank in the direction of the correcting roll, even though he is again wings-level. At this point he has the leans; and although he may be able to fly the aircraft properly by the very deliberate and difficult process of forcing the attitude indicator to read correctly, his illusion can last for many minutes, seriously degrading his flying efficiency during that time.

Interestingly, pilots frequently get the leans after prolonged turning maneuvers, and not because of alternating subthreshold and suprathreshold angular motion stimuli. In a holding pattern, for example, the pilot rolls into a 3-degree/s standard-rate turn, holds the turn for 1 min, rolls out and flies straight and level for 1 min, turns again for 1 min, and so on until traffic conditions permit him to proceed toward his destination. During the turning segments the pilot initially feels the roll into the turn and accurately perceives the banked attitude. But as the turn continues, his percept of being in a banked turn dissipates and is replaced by a feeling of flying straight and level, both because the sensation of turning is lost when the endolymph comes up to speed in the semicircular ducts (somatogyral illusion) and because the net G force being directed toward the floor of the aircraft provides a false cue of verticality (somatogravic illusion). When the pilot then rolls out of the turn, he feels he has rolled into a banked turn in the opposite direction. With experience, a pilot learns to suppress this false sensation quickly by paying strict attention to the attitude indicator. Sometimes, however, the pilot finds he cannot dispel the illusion of banking--usually when he is particularly busy, unfortunately. The leans can also be caused by misleading peripheral visual orientation cues, as mentioned in the discussion of the visual illusions. Roll angular vection is particularly effective in this regard, at least in the laboratory. One thing about the leans is obvious: there is no single explanation for it. The deficiencies of several orientation-sensing systems in some cases reinforce each other to create an illusion; in other cases the inaccurate information from one sensory modality for some reason is selected over the accurate information from others to create the illusion. Stories have surfaced of pilots suddenly experiencing the leans for no apparent reason at all, or even of experiencing it voluntarily by imagining the earth to be in a different direction from the aircraft. The point is that one must not think that the leans, or any other illusion for that matter, occurs as a totally predictable response to a physical stimulus: there is much more to perception than stimulation of the end-organs.

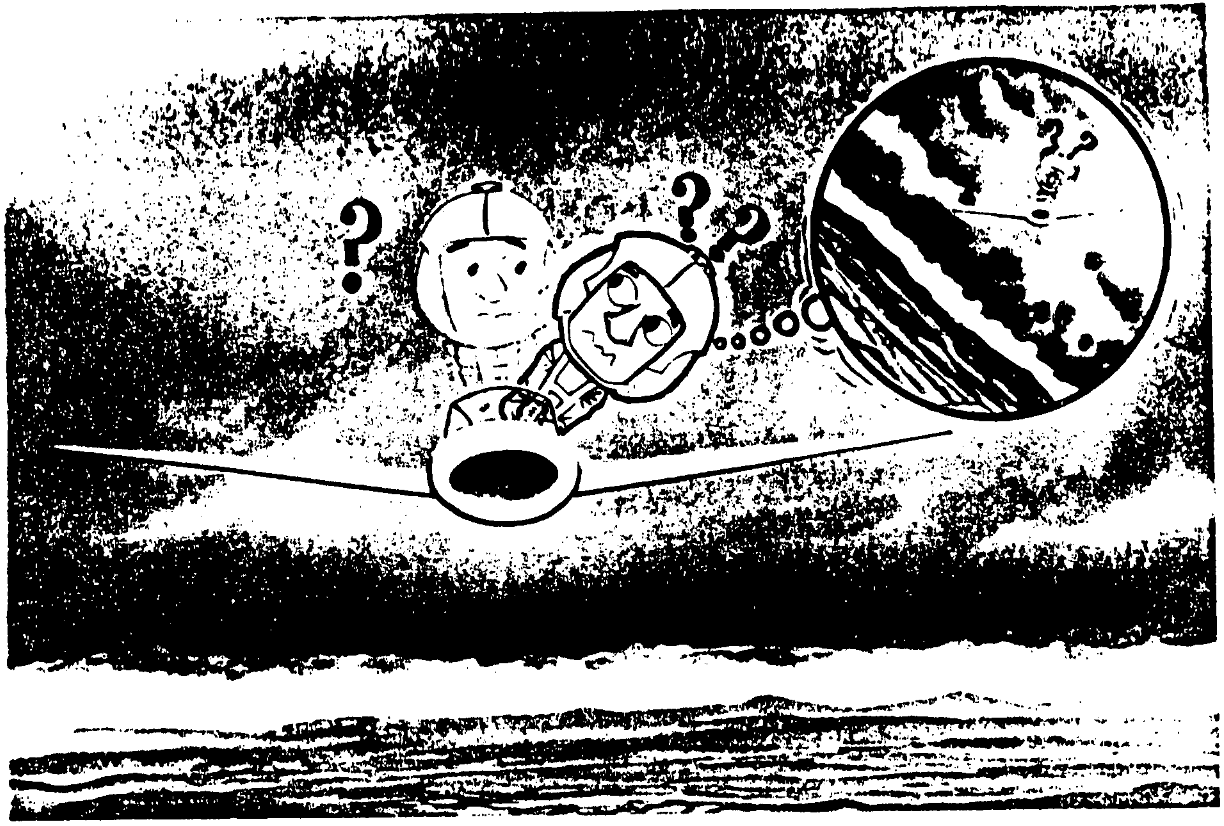


Figure 22. The leans, the most common of all vestibular illusions in flight. Falsely perceiving himself to be in a right bank, but flying the aircraft straight and level by means of the flight instruments, this pilot is leaning to the left in an attempt to assume an upright posture compatible with his illusion of bank.

Disorientation in Flight

Definitions. We have already defined an orientational illusion to be a false percept of position, attitude, or motion, relative to the plane of the earth's surface. Spatial disorientation and the equivalent term, pilot vertigo, are usually taken to mean the experiencing of an orientational illusion in flight. There is a major qualitative difference, however, between simply experiencing an orientational illusion and having to control an aircraft under conditions of misperceived or conflicting orientation cues. Furthermore, this difference becomes very important in the analysis of mechanisms involved in aircraft mishaps due to orientational illusions, and in the development of training aids for educating pilots about the potential for loss of aircraft control while under the influence of orientational illusions. For those reasons, we find it necessary to restrict the use of the term spatial disorientation to the condition wherein one not only has an orientational illusion but also needs to have correct perception of orientation for controlling his position, attitude, or motion. When one has an orientational illusion but has no need for correct information about his orientation, we say he has spatial unorientation. This distinction is exemplified by the contrast between the experience of a pilot, who must fly his vehicle on a desired path through space by responding to available orientation cues (and to whom such cues are, therefore, highly relevant), and the experience of an airborne communications monitor, who can perform his duty without regard to his spatial orientation (and to whom orientation cues--whether true or false--are essentially irrelevant). Obviously, it is spatial disorientation, not spatial unorientation, that causes aircraft mishaps and warrants investigative and educational efforts to prevent it.

Types. It is also useful to make the distinction between unrecognized (also called Type I) and recognized (Type II) spatial disorientation. As the term implies, unrecognized spatial disorientation refers to the situation in which a pilot, oblivious to the fact that he is disoriented, controls his vehicle completely in accord with and in response to his false orientational percept. In recognized spatial disorientation the pilot realizes something is wrong with his ability to fly the vehicle, but he may or may not actually realize that the source of his problem is spatial disorientation. Even further out in the spectrum of types of disorientation is that in which the pilot not only recognizes that he cannot control his vehicle effectively because of spatial disorientation, but he also cannot obtain correct information because the violence of the motion imposed is blurring his vision with counterproductive vestibulo-ocular reflexes (nystagmus). For want of an adequately descriptive simple term, we shall call this type vestibulo-ocular disorganization, or Type III spatial disorientation.

Examples. The last of four F-15 Eagle fighter aircraft took off on a daytime sortie in weather, intending to follow the other three in a radar in-trail departure. Because of a navigational error committed by the pilot shortly after takeoff, he was unable to acquire the other aircraft on his radar. Frustrated, he elected to intercept the other aircraft where he knew they would be in the arc of the standard instrument departure; so he made a bee-line for that point, presumably scanning his radar diligently for the blips he knew should be appearing at any time. Meanwhile, after ascending to 1200 m (4000 ft) above ground level, he entered a descent of approximately 12 m/s (2400 ft/min) as a result of an unrecognized 3-degrees-nose-low attitude. After receiving requested position information from another member of the flight, the mishap pilot suddenly realized he was in danger of colliding with the others, or he suddenly acquired them on radar: he then made a steeply banked turn, either to avoid a perceived threat of collision or to join up with the rest of the flight. Unfortunately, he had by this time descended far below the other aircraft and was going too fast to avoid the ground, which became visible under the overcast just before the aircraft crashed. This mishap resulted from an episode of unrecognized, or Type I, disorientation. The specific illusion responsible appears to have been the somatogravic illusion, created by the forward acceleration of this high-performance aircraft during takeoff and climb-out. The pilot's preoccupation with the radar task compromised his instrument scan to the point where the false vestibular cues were able to penetrate his orientational information processing. Having unknowingly accepted an inaccurate orientational percept, he controlled the aircraft accordingly until it was too late to recover.

Examples of recognized, or Type II, spatial disorientation are easier to obtain than are examples of Type I, as most experienced pilots have anecdotes to tell about how they "got vertigo" and fought it off. Some pilots were not so fortunate, however. One F-15 Eagle pilot, after climbing his aircraft in formation with another F-15 at night, began to experience difficulty maintaining spatial orientation and aircraft control upon leveling off in clouds at 8200 m (27,000 ft). "Talk about practice bleeding," he commented to the lead pilot. Having decided to go to another area because of the weather, the two pilots began a descending right turn. At this point the pilot on the wing told the lead pilot, "I'm flying upside down." Shortly afterward the wingman considered separating from the formation, saying, "I'm going lost wingman;" then, "No, I've got you;" and finally, "No, I'm going lost wingman." The mishap aircraft then descended in wide spiral, crashing into the desert less than a minute later, even though the lead pilot advised the wingman several times during the descent to level out. In this mishap the pilot probably suffered an inversion illusion upon leveling off in the weather, and entered a graveyard spiral after leaving the formation. Although he knew he was disoriented, or at least recognized the possibility, he still was unable to control the aircraft effectively. That a pilot can realize he is disoriented, see accurate orientation information displayed on the attitude indicator, and still fly into the ground, always strains the credulity of nonaviators. Pilots who have had spatial disorientation, who have experienced fighting oneself for control of an aircraft, are less skeptical.

The pilot of an F-15 Eagle, engaged in vigorous air combat tactics training with two other F-15s on a clear day, initiated a hard left turn at 5200 m (17,000 ft) above ground level. For reasons that have not been established with certainty, his aircraft began to roll to the left at a rate estimated at 150 to 180 degrees/s. He transmitted, "Out-of-control autoroll," as he descended through 4600 m (15,000 ft). The pilot made at least one successful attempt to stop the roll, as evidenced by the momentary cessation of the roll at 2400 m (8,000 ft); then the aircraft began to roll again to the left. Forty seconds elapsed between when the rolling began and when the pilot ejected--but too late. Regardless of whether the rolling was caused by a mechanical malfunction or was induced by the pilot himself, the certain result of this extreme motion was vestibulo-ocular disorganization, which not only prevented the pilot from reading his instruments but also kept him from orienting with the natural horizon. Thus, Type III disorientation probably prevented him from taking appropriate corrective action to stop the roll and keep it stopped; if not that, it certainly compromised his ability to assess accurately the level to which his situation had deteriorated.

Statistics. Despite continuing efforts to educate pilots about spatial disorientation and the real hazard it represents, the fraction of aircraft mishaps caused by or contributed to by spatial disorientation remained fairly constant over the three decades between 1950 and 1980. A number of statistical studies of spatial disorientation mishaps bear this out for the United States Air Force. In 1956 Nuttall and Sanford reported that, in one major air command during the period 1954-1956, spatial disorientation was responsible for 4% of all major aircraft mishaps and 14% of all fatal aircraft mishaps.[14] Moser in 1969 reported a study of aircraft mishaps in another major air command during the four-year period, 1964-1967: he found that spatial disorientation was a significant factor in 9% of major mishaps and 26% of fatal mishaps.[15] In 1971 Barnum and Bonner reviewed the Air Force mishap data from 1958 through 1968, and found that in 281 or 6% of the 4,679 major mishaps, spatial disorientation was a causative factor; fatalities occurred in 211 of those 281, accounting for 15% of the 1,462 fatal mishaps.[16] A comment by Barnum and Bonner summarizes some interesting data about the "average pilot" involved in a spatial disorientation mishap: "He will be around 30 years of age, have 10 years in the cockpit, and have 1,500 hours of first pilot/instructor-pilot time. He will be a fighter pilot and will have flown approximately 25 times in the three months prior to his accident." Barnum next analyzed the mishap data for the three-year period, 1969-1971, and concluded that spatial disorientation mishaps again accounted for 6% of major mishaps, but only for 10% of fatal mishaps during this period.[17] In a 1973 study, Kellogg found the relative incidence of Air Force spatial disorientation mishaps in the years 1968 through 1972 to range from 4.8 to 6.2%, and confirmed the high proportion of fatalities in mishaps resulting from spatial disorientation.[18] In 1980 Gillingham and Page (unpublished data) reviewed the Air Force aircraft mishaps of 1979 and determined that at least 9 of the 94 major mishaps (9.6%) and 9 of the 49 fatal mishaps (18.4%) occurring that year would not have occurred had the pilots not been spatially disoriented at some time during the mishap sequence. The cost of the Air Force aircraft destroyed each year in disorientation mishaps has been until recently on the order of $20 million per year. In 1979 it was $40 million; and the figure continues to rise, mainly as a result of the rapidly rising cost of new military aircraft. Statistics on the incidence of disorientation-related aircraft mishaps in the United States Army and Navy (7.11% and 6.75% of total mishaps, respectively)[19,20] are remarkably similar to those of the air force, even though the flying missions of the several military services are somewhat different.

Although statistics indicating the relative frequency of spatial disorientation mishaps in air-carrier operations are not readily available, it would be a serious mistake to conclude that there have been no air-carrier mishaps caused by spatial disorientation. Fourteen such mishaps occurring between 1950 and 1969 were reportedly due to somatogravic and visual illusions resulting in the so-called "dark-night-takeoff accident."[9] In addition, 26 commercial airliners were involved in jet-upset incidents or accidents during the same period.[11] Spatial disorientation is also a problem in general (non-military, non-air-carrier) aviation. Kirkham et al. reported in 1978 that, although spatial disorientation is a cause or factor in only 2.5% of all general aviation aircraft accidents in the United States, it is the third most common cause of fatal general aviation accidents: 627 of the 4,012 fatal mishaps (15.6%) occurring in the years 1970 through 1975 involved spatial disorientation as a cause or factor.[21] Furthermore, the contribution of spatial disorientation to the second most common cause of fatal general aviation accidents--continued VFR flight into adverse weather--is undoubtedly highly significant. Notably, 90% of general aviation mishaps in which disorientation is a cause or factor are fatal.

Dynamics of Spatial Orientation and Disorientation. It is naive to assume that a certain pattern of physical stimuli always elicits a particular veridical or illusory perceptual response. Certainly, when a pilot has a wide, clear view of the horizon, ambient vision supplies virtually all of his orientation information; and potentially misleading linear or angular acceleratory motion cues do not result in spatial disorientation (unless, of course, they are so violent as to cause vestibulo-ocular disorganization). When a pilot's vision is compromised by weather, the same acceleratory motion cues can cause him to develop spatial disorientation, but he usually avoids it by referring to his aircraft instruments for orientation information. If the pilot is unskilled at interpreting the instruments, or if the instruments fail, those misleading motion cues inevitably cause disorientation. Such is the character of visual dominance, the phenomenon wherein one incorporates visual orientation information into his percept of spatial orientation, to the exclusion of vestibular and nonvestibular proprioceptive, tactile, and other sensory cues. Visual dominance falls into two categories: the congenital type, in which ambient vision provides dominant orientation cues through natural neural connections and functions; and the acquired type, in which orientation cues are gleaned through focal vision and are integrated as a result of training and experience into an orientation percept. The functioning of the proficient instrument pilot illustrates acquired visual dominance: he has learned to decode with foveal vision the information on the attitude indicator and other flight instruments and to reconstruct that information into a concept of where he is, what he is doing, and where he is going; and he refers to that concept when controlling his aircraft. This complex skill must be developed through training and maintained through practice; and it is the fragility of this acquired visual dominance that makes spatial disorientation such a hazard.

The term *vestibular suppression* is often used to denote the active process of visually overriding undesirable vestibular sensations or vestibulo-ocular reflexes. An example of this aspect of visual dominance is seen in well-trained figure skaters who, with much practice, learn to abolish the post-rotatory dizziness and nystagmus that normally result from the very high angular decelerations associated with suddenly stopping rapid spins on the ice.[22] But even these individuals, when deprived of vision by eye closure or darkness, have the very dizziness and nystagmus we would expect to result from the acceleratory stimuli generated.[23] In flight, the ability to suppress unwanted vestibular sensations and reflexes is developed with repeated exposure to the linear and angular accelerations of flight. As is the case with the figure skaters, however, the pilot's ability to prevent vestibular sensations and vestibulo-ocular reflexes is compromised when he is deprived of visual orientation cues--when he must look away from his attitude indicator to manipulate a radio frequency-selector knob, for instance.

At this point, we introduce the concept of *vestibular opportunism*. By this is meant the propensity of the vestibular system to fill an orientation-information void swiftly and surely with vestibular information. When a pilot flying in instrument weather looks away from his artificial horizon for a mere few seconds, this is usually long enough for erroneous vestibular information to break through the pilot's defenses and become incorporated into his orientational percept. In fact, conflicts between focal visual and vestibular sources of orientation information tend to resolve themselves very quickly in favor of the vestibular information, without providing the pilot an opportunity to evaluate the information. It would seem that any orientation information reaching the vestibular nuclei--whether vestibular, other proprioceptive, or ambient visual--should have an advantage in competing with focal visual cues for expression as the pilot's sole orientational percept, because the vestibular nuclei are primary terminals in the pathways for reflex orientational responses, and are the initial level of integration for any eventual conscious concomitant of perception of spatial orientation. In other words, although acquired visual dominance can be maintained by diligent attention to artificial orientation cues, the challenge to this dominance presented by the processing of natural orientation cues through primitive channels is very potent and ever present.

The lack of adequate orientation cues, and conflicts between competing sensory modalities, are only a part of the whole picture of a disorientation mishap. Why so many disoriented pilots, even those who know they are disoriented, are unable to recover their aircraft has mystified aircraft accident investigators for decades. There are two possible explanations for this phenomenon. The first suggests that the psychologic stress of disorientation results in a disintegration of higher-order learned behavior, including flying skills. The second describes a complex psychomotor effect of disorientation that causes the pilot to feel the aircraft itself is misbehaving.

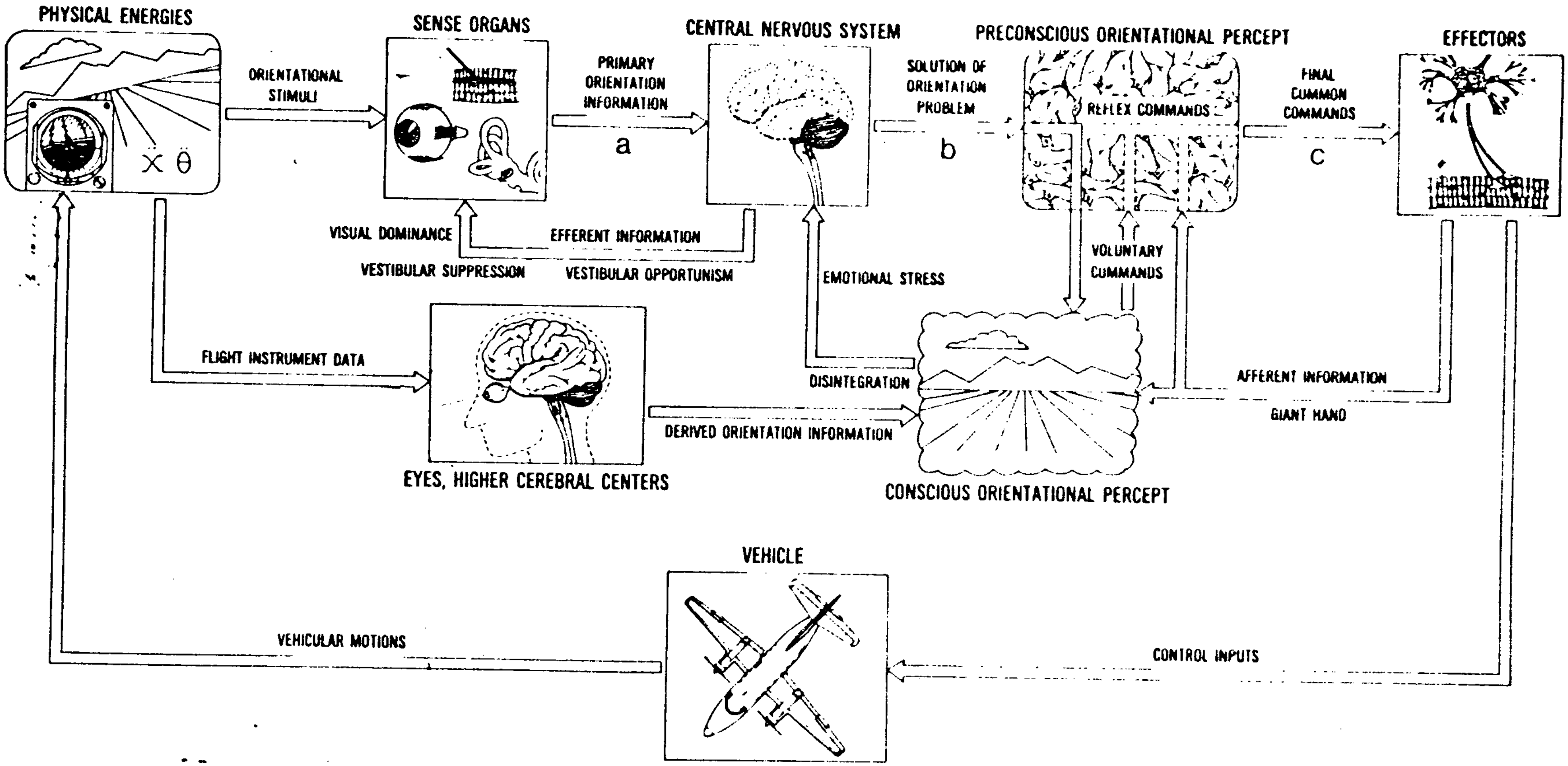
The disintegration of flying skill perhaps begins with the pilot's realization that his spatial orientation and control over the motion of his aircraft have been compromised. Under such circumstances, he pays more heed to whatever orientation information is naturally available, monitoring it more and more vigorously. Whether the brain stem reticular activating system or the vestibular efferent system, or both, are responsible for the resulting heightened arousal and enhanced vestibular information flow can only be surmised; but the net effect is that more erroneous vestibular information is processed and incorporated into the pilot's orientational percept. This, of course, only makes matters worse. A positive-feedback situation is thus encountered, and the vicious circle can now be broken only with a precisely directed, and very determined, effort by the pilot. Unfortunately, complex cognitive and motor skills tend to be degraded under conditions of psychologic stress such as occurs during Type II or Type III spatial disorientation. First, there is a coning of attention. Pilots who have survived severe disorientation have reported they were concentrating on one particular flight instrument instead of scanning and interpreting the whole group of them in the usual manner. Pilots have also reported they were unaware of radio transmissions to them while they were trying to recover from disorientation. Second, there is the tendency to revert to more primitive behavior, even reflex action, under conditions of severe psychologic stress. The highly developed, relatively newly acquired skill of instrument flying can give way to primal protective responses during disorientation stress, making appropriate recovery action unlikely. Third, it is often suggested that disoriented pilots become totally immobilized--frozen to the aircraft controls by fear or panic--as the disintegration process reaches its final state.

The giant hand phenomenon, described by Malcolm and Money,[11] undoubtedly explains why many pilots have been rendered hopelessly confused and ineffectual by spatial disorientation, even though they knew they were disoriented and should have been able to avoid losing control of their aircraft. The pilot suffering from this effect of disorientation perceives falsely that his aircraft is not responding properly to his control inputs, because every time he tries to bring the aircraft to the desired attitude, it seems actively to resist his effort and fly back to another, more stable, attitude. A pilot experiencing disorientation about the roll axis (e.g., the leans or graveyard spiral) may feel a force--like a giant hand--trying to push one wing down and hold it there, while the pilot with pitch-axis disorientation (e.g., the classic somatogravic illusion) may feel the airplane subjected to a similar force trying to hold the nose down. Pilots who are unaware of the existence of this phenomenon and experience it for the first time can be very surprised and confused by it, and may not be able to discern the exact nature of their problem. A pilot's radio transmission that the aircraft controls are malfunctioning should not, therefore, be taken as conclusive evidence that a control malfunction caused a mishap: spatial disorientation could have been the real cause.

What mechanism could possibly explain the giant hand? To try to understand this phenomenon, we must first recognize that our perception of orientation results not only in the conscious awareness of our position and motion but also in a preconscious percept needed for proper performance of voluntary motor activity and reflex actions. A conscious orientational percept can be considered rational, in that we can subject it to intellectual scrutiny, weigh the evidence for its veracity, conclude that it is inaccurate, and to some extent modify the percept to fit facts obtained from other than the primary orientation senses. In contrast, a preconscious orientational percept must be considered irrational, in that it consists only of an integration of data relayed to the brain stem and cerebellum by the primary orientation senses, and is not amenable to modification by reason. So what happens when a pilot knows he has become disoriented and tries to control his aircraft by reference to a conscious, rational percept of orientation which is at variance with his preconscious, irrational one? Because only the data comprising one's preconscious orientational percept are available for the performance of primitive orientational reflexes (e.g., vestibulo-ocular and postural reflexes), high-order reflexes (e.g., aversive responses), and skilled voluntary motor activity (e.g., walking, running, bicycling, driving, flying), we should expect the actual outcome of these types of actions to deviate from the rationally intended outcome whenever the orientational data upon which they depend are different from the rationally perceived orientation. The disoriented pilot who consciously commands a roll to recover aircraft control, while the informational substrate in reference to which his body functions indicates that such a move is counterproductive or even dangerous, may experience a great deal of difficulty in executing the command. Or he may discover that the roll, once accomplished, must be reaccomplished repeatedly, as his body responds automatically to the preconsciously perceived orientational threat resulting from his conscious efforts and actions to regain control. Thus, the preconscious orientational percept influences Sherrington's "final common pathway" for both reflex and voluntary motor activity; and the manifestation of this influence on the act of flying during an episode of spatial disorientation is the giant hand phenomenon. To prevail in this conflict between his will and his skill, the pilot must decouple his voluntary acts from his previously learned flying behavior, by accomplishing those motions which produce directly the desired readings of the flight instruments, rather than by flying the airplane to an attitude corresponding to the desired readings of the flight instruments.

The salient features of the dynamics of spatial orientation and disorientation are diagrammed in Figure 23; the concepts of visual dominance, vestibular suppression, vestibular opportunism, disintegration of flying skill, conscious and preconscious orientational percepts, and the giant hand phenomenon are presented therein as they relate to the overall scheme of orientation-information processing.

Figure 23. Flow of orientation information in flight. The primary information-flow loop involves: stimulation of the visual, vestibular, and other orientation senses by visual scenes and linear and angular accelerations; processing of this primary orientation information by brain stem, cerebellum, and lower cerebral centers; incorporating the solution into a data base for reflexive and skilled voluntary motor activity (preconscious orientational percept); and effecting control inputs, which produce aircraft motions that result in orientational stimuli. A secondary path of information flow involves the processing of largely numerical data from flight instruments into derived orientation information by higher cerebral centers. Subloop a provides for feedback between various components of the nervous system, and includes efferent system influences on the sensory end-organs themselves. The phenomena of visual dominance, vestibular suppression, and vestibular opportunism occur in conjunction with the functioning of this loop. Subloop b generates conscious perception of orientation, both from the body's naturally obtained solution of the orientation problem and from orientation information derived from flight instrument data. Voluntary control commands arise in response to conscious orientational percepts; and the psychic stress resulting from conflicting orientation information or from apparently aberrantly responding effectors can influence the manner in which orientation information is processed, leading ultimately to disintegration of flying skill. Subloop c incorporates feedback from muscles, tendons, and joints involved in making control inputs, and provides a basis for the giant hand phenomenon.


PHYSICAL ENERGIES
Ẍ θ̈
ORIENTATIONAL STIMULI
SENSE ORGANS
PRIMARY ORIENTATION INFORMATION
a
CENTRAL NERVOUS SYSTEM
SOLUTION OF ORIENTATION PROBLEM
b
PRECONSCIOUS ORIENTATIONAL PERCEPT
REFLEX COMMANDS
FINAL COMMON COMMANDS
c
EFFECTORS
VISUAL DOMINANCE
EFFERENT INFORMATION
VESTIBULAR SUPPRESSION
VESTIBULAR OPPORTUNISM
EMOTIONAL STRESS
VOLUNTARY COMMANDS
FLIGHT INSTRUMENT DATA
DISINTEGRATION
AFFERENT INFORMATION
GIANT HAND
DERIVED ORIENTATION INFORMATION
EYES, HIGHER CEREBRAL CENTERS
CONSCIOUS ORIENTATIONAL PERCEPT
VEHICLE
VEHICULAR MOTIONS
CONTROL INPUTS

Conditions Conducive to Disorientation. From a knowledge of the physical bases of the various illusions of flight one can readily infer many of the specific environmental factors conducive to spatial disorientation. Certain visual phenomena produce characteristic visual illusions, such as false horizons, linear and angular vection, and autokinesis. Prolonged turning at a constant rate, as in a holding pattern or procedure turn, can precipitate somatogyral illusions or the leans; and Coriolis illusions can conceivably occur with head movements under these conditions. Relatively sustained linear accelerations, such as those that occur on takeoff, can produce somatogravic illusions; and head movements during G-pulling turns can elicit G-excess illusions.

What are the regimes of flight and activities of the pilot that seem most likely to allow these potential illusions to manifest themselves? Certainly, instrument weather and night flying are primary factors. But especially likely to produce disorientation is the practice of switching back and forth between the instrument flying mode and the visual or contact flying mode; a pilot is far less likely to become disoriented if he gets on the instruments as soon as out-of-cockpit vision is compromised and stays on the instruments until continuous contact flying is again assured. In fact, any event or practice requiring the pilot to break his instrument cross-check is conducive to disorientation. In this regard, avionics control switches and displays in some aircraft are located where the pilot must interrupt his instrument cross-check for more than a few seconds to interact with them, and are thus known (not so affectionately) as "vertigo traps." Some of these vertigo traps require substantial movements of the pilot's head during the time his cross-check is interrupted, thereby providing both a reason and an opportunity for spatial disorientation to strike.

Formation flying in weather is probably the most likely of all situations to produce disorientation; indeed, some experienced pilots get disoriented every time they fly wing or trail in weather. The fact that a pilot has little if any opportunity to scan his flight instruments while flying formation on his lead aircraft in weather means he is essentially isolated from any source of accurate orientation information, and misleading vestibular and ambient visual cues arrive unchallenged into his sensorium.

Of utmost importance to a pilot in preventing spatial disorientation is competency and currency in instrument flying. A non-instrument-rated pilot who penetrates instrument weather is virtually assured of developing spatial disorientation within a matter of seconds, just as the most competent instrument pilot would develop it if he found himself flying in weather without functioning flight instruments. Regarding instrument flying skill, one must "use it or lose it," as they say. For that reason pilots whose primary flying activity involves missions or environments in which instrument weather is rarely encountered (e.g., air combat training in the United States Southwest) must aggressively seek opportunities to practice instrument flying so as to maintain their proficiency at it. Otherwise, they could discover that their instrument flying skill has deteriorated to a dangerously low level during a rare occasion when that skill is really needed.

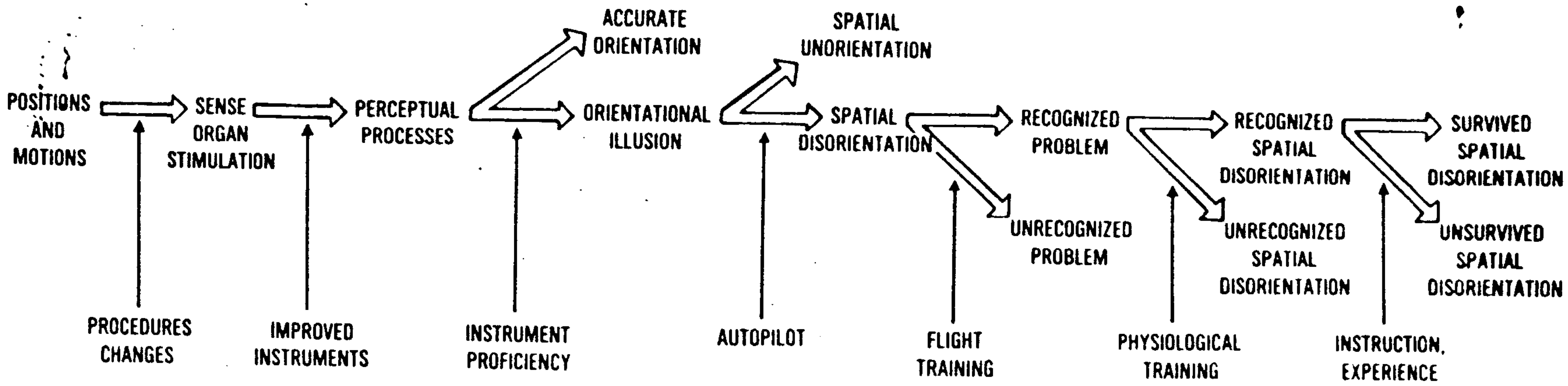
Finally, conditions affecting the pilot's physical or mental health must be considered capable of rendering the pilot more susceptible to spatial disorientation. The unhealthy effect of alcohol ingestion on neural information processing is one obvious example; but the less well-known ability of alcohol to produce vestibular nystagmus (positional alcohol nystagmus--PAN) for many hours after its more overt effects have disappeared is probably of equal significance. Other drugs, such as barbiturates, amphetamines, and even the quinine in tonic water, are suspected of possibly have contributed to aircraft mishaps resulting from spatial disorientation. Likewise, physical and mental fatigue, as well as acute or chronic emotional stress, can rob the pilot of his ability to concentrate on his instrument cross-check, and can therefore have deleterious effects on his resistance to spatial disorientation.

Prevention of Disorientation Mishaps

Spatial disorientation can be attacked in several ways. Theoretically, each link in the physiologic chain of events leading to a disorientation mishap can be broken by a specific countermeasure (Fig. 24). Spatial disorientation can many times be prevented by modifying flying procedures so as to avoid those visual or vestibular stimuli that tend to create illusions in flight. By improving the capacity of flight instruments to translate aircraft position and motion information into readily assimilable orientation cues, we can help the pilot avoid disorientation. Through repeated exposure to the environment of instrument flight, the pilot becomes proficient in instrument flying; this involves developing perceptual processes that result in accurate orientational percepts rather than orientational illusions. If a pilot who is experiencing an illusion can relinquish control of his aircraft to an autopilot, he can convert his situation from one of hazardous spatial disorientation to one of irrelevant spatial unorientation, and reclaim control once the orientational illusion has subsided. Use of the autopilot, not only to help the pilot recover from disorientation, but also to help prevent it in the first place, is a technique that has considerable potential for saving lives, particularly in general aviation. Given that a pilot has developed spatial disorientation, if he can be made to recognize that he is disoriented, he is halfway along the road to recovery.

To recognize disorientation is not necessarily easy, however. First, the pilot must recognize that he is having a problem holding his altitude or heading; this he cannot do if he is concentrating on something other than the fight instruments--on the radar scope, for instance. Only through proper flight training can the discipline of continuously performing the instrument cross-check be instilled. Second, the pilot must recognize that his difficulty in controlling the aircraft is a result of spatial disorientation. This ability is promoted through physiological training. We said that the pilot who suspects he is disoriented is halfway down the road to recovery: why not most of the way? Because a pilot's ability to cope with the effects of disorientation on his control inputs to the aircraft comes through effective flight instruction, proper physiological training, and experience in controlling his vehicle in an environment of conflicting orientation cues--his simply being aware that he is disoriented by no means ensures his survival.

Figure 24. The chain of events leading to a spatial disorientation mishap, and where the chain can be attacked and broken. From left: Flight procedures can be altered to generate less confusing sensory inputs. Improved instrument presentations can aid assimilation of orientation cues. Proficiency in instrument flying helps assure accurate orientational percepts. In the event the pilot suffers an orientational illusion, having the aircraft under autopilot control avoids disorientation by substituting unorientation. Proper flight training allows the disoriented pilot to recognize he is having a problem controlling his craft. Once he knows he is having a problem, his physiological training helps him realize his problem is spatial disorientation. With appropriate instruction and/or firsthand experience, the pilot with recognized spatial disorientation can apply the correct control forces to recover the aircraft and survive the disorientation incident.


POSITIONS AND MOTIONS
SENSE ORGAN STIMULATION
PERCEPTUAL PROCESSES
ACCURATE ORIENTATION
ORIENTATIONAL ILLUSION
SPATIAL UNORIENTATION
SPATIAL DISORIENTATION
RECOGNIZED PROBLEM
UNRECOGNIZED PROBLEM
RECOGNIZED SPATIAL DISORIENTATION
UNRECOGNIZED SPATIAL DISORIENTATION
SURVIVED SPATIAL DISORIENTATION
UNSURVIVED SPATIAL DISORIENTATION
PROCEDURES CHANGES
IMPROVED INSTRUMENTS
INSTRUMENT PROFICIENCY
AUTOPILOT
FLIGHT TRAINING
PHYSIOLOGICAL TRAINING
INSTRUCTION, EXPERIENCE

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Education and Training. Physiological training is the main weapon against spatial disorientation at the disposal of the flight surgeon and aerospace physiologist. This training ideally should consist of both didactic material and demonstrations. There is no paucity of didactic material on the subject of disorientation: at least eight films, five videocassette tapes, three slide sets, two handbooks, and numerous chapters in books and manuals have been prepared for the purpose of informing the pilot about the mechanisms and hazards of spatial disorientation. Although the efforts to generate information on spatial disorientation are commendable, there has been a tendency for the didactic material thus far produced to dwell too much on mechanisms and effects of disorientation without giving much practical advice on how to deal with it. Money and Malcolm noted that none of the available films on spatial disorientation gives sufficient emphasis to what the pilot should do when he suspects disorientation.[24] While several of the films recommend that the pilot believe his instruments, this message is too subdued and, by itself, is inadequate. Money and Malcolm argue that under some circumstances (e.g., panic) a pilot may in fact believe the instruments but continue to fly the aircraft according to his false orientational percept. If a pilot is told in addition, "Make the instruments read right, regardless of your sensations," he has simple, definite instructions on how to bring the aircraft under control when disorientation strikes. We strongly advise, therefore, that every presentation to pilots on the subject of spatial disorientation emphasize the need to *make the instruments read right*, as well as to believe them, when responding to disorientation stress.

The traditional demonstration accompanying lectures to pilots on spatial disorientation is a ride on a Barany chair or other smoothly rotating device. The subject, sitting in the device with his eyes closed, is accelerated to a constant angular velocity and asked to signal with his thumbs his perceived direction of turning. After a number of seconds (usually from 10 to 20) at constant angular velocity, the subject loses the sensation of rotation and signals this fact to the observers. Then the instructor suddenly stops the rotation, whereupon the subject immediately indicates that he feels he is turning in the direction opposite his original direction of rotation. The subject is usually asked to open his eyes during this part of the demonstration, and is amazed to see that he is actually not turning, despite the strong vestibular sensation of rotation. After the described demonstration of somatogyral illusions, the subject is again rotated at a constant velocity with his eyes closed, this time with head down (facing the floor). When the subject indicates his sensation of turning has ceased, he is asked to raise his head abruptly so as to face the wall. The Coriolis illusion resulting from this maneuver is one of a very definite roll to one side: the startled subject may exhibit a protective postural reflex, and may open his eyes to help him visually orient during his falsely perceived upset. The message delivered with these demonstrations is not that such illusions will be experienced in flight in the same manner, but that the vestibular sense can be fooled--i.e., is unreliable--and that only the flight instruments provide accurate orientation information.

Over the years at least a dozen different devices have been developed to augment or supplant the Barany chair for demonstrating various vestibular and visual illusions and the effects of disorientation in flight. These devices, collectively known as *antivertigo trainers*, fall into two basic categories: *orientational illusion demonstrators* and *spatial disorientation demonstrators*. The great majority are illusion demonstrators, in which the subject rides passively and experiences one or more of the following: somatogyral, oculogyral, somatogravic, oculogravic, Coriolis, G-excess, vection, and autokinetic illusions. In an illusion demonstrator, the subject typically is asked to record or remember the magnitude and direction of the orientational illusion, and then is told or otherwise allowed to experience his true orientation. A few antivertigo trainers are actually spatial disorientation demonstrators, which allow the subject to experience the difficulty in controlling the attitude and motion of the trainer while being subjected to somatogravic, somatogyral, and/or Coriolis illusions. Figure 25 shows two antivertigo trainers presently in use in the United States Air Force. One must be aware that the name given to any particular antivertigo trainer does not necessarily describe its function: The USAFSAM Spatial Disorientation Demonstrator, for example, was actually an orientational illusion demonstrator.

Although the maximum use of antivertigo trainers in physiological training of pilots is to be encouraged, it is important to recognize the great potential for misuse of such devices by personnel not thoroughly trained in their theory and function. Several antivertigo trainers have aircraft-instrument tracking tasks for the subject to perform while he is experiencing orientational illusions but is not actually controlling the motion of the trainer. The temptation is very strong for unsophisticated operating personnel to tell the subject he is "fighting disorientation" if he performs well on the tracking task while subjected to the illusion-generating motions. Because the subject's real orientation is irrelevant to the tracking task, any orientational illusion is also irrelevant, and he experiences no conflict between visual and vestibular information in acquiring cues upon which to base his control responses. This situation, of course, does not capture the essence of disorientation in flight; and the trainee who is led to believe he is fighting disorientation in such a ground-based demonstration may develop a false sense of security about his ability to combat disorientation in flight. The increasing use of spatial disorientation demonstrators, in which the subject must control the actual motion of the trainer by referring to true-reading instruments while under the influence of orientational

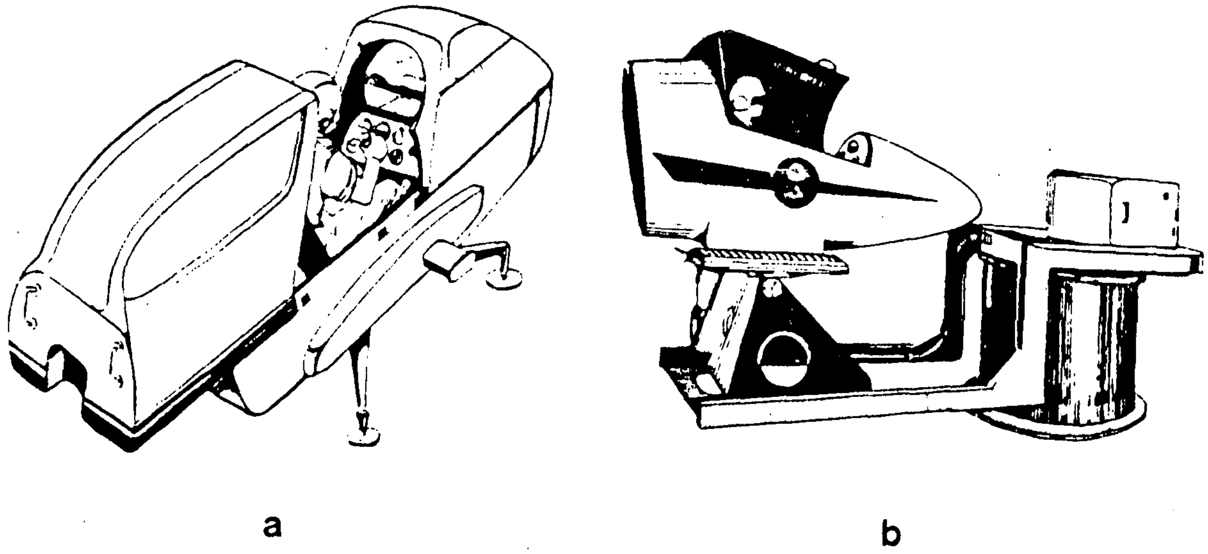

Figure 25. Two types of antivertigo trainer currently in use: a. The Vertigon®, an orientational illusion demonstrator, allows the subject to experience Coriolis and somatogyral illusions while performing tracking and dial-setting tasks. b. The Vertifuge®, a spatial disorientation demonstrator, subjects the trainee to somatogravic, Coriolis, and somatogyral illusions that generate orientational conflicts as he tries to control the attitude and motion of the device by referring to a true-reading attitude indicator.

illusions, will most likely reduce the potential for misuse and will improve the effectiveness of presentations to pilots on the subject of spatial disorientation.

Flight training provides a good opportunity to instruct pilots about the hazards of spatial disorientation. Inflight demonstrations of vestibular illusions are included in most formalized pilot training curricula, although the efficacy of such demonstrations is highly dependent on the motivation and skill of the individual flight instructor. Somatogyral and somatogravic illusions and illusions of roll attitude can usually be induced in a student pilot by a flight instructor who either understands how the vestibular system works or knows from experience which maneuvers consistently produce illusions. The vestibular-illusion demonstration should not be confused with the unusual-attitude-recovery demonstrations in the typical pilot training syllabus: the objective of the former is for the student to experience orientational illusions and recognize them as such; that of the latter is for the student to learn to regain control of an aircraft in a safe and expeditious manner. In both types of demonstration, however, control of the aircraft should be handed over to the student pilot with the instruction, "Make the instruments read right."

Part of flight training is continuing practice to maintain flying proficiency, and the importance of such practice in reducing the likelihood of having a disorientation mishap cannot be overemphasized. Whether flying on instruments, in formation, or engaged in aerobatic maneuvering, familiarity with the environment--based on recent exposure to it--and proficiency at the flying task--based on recent practice at it--result not only in a greater ability to avoid or dispel orientational illusions, but also in a greater ability to cope with disorientation when it does occur.

Inflight Procedures. If a particular inflight procedure frequently results in spatial disorientation, it stands to reason that modifying or eliminating that procedure should help reduce aircraft mishaps due to disorientation. Night formation takeoffs and rejoins are examples of inflight procedures that very frequently are associated with spatial disorientation; and the United States Air Force has, wisely, officially discouraged these practices in most of its major commands.

Another area of concern is the "lost wingman" procedure, used when a pilot has lost sight of the aircraft on which he has been flying wing. Usually the loss of visual contact is due to poor visibility, and occurs after a period of vacillation between formation flying and instrument flying. Such conditions, of course, invite disorientation. The lost wingman procedure must, therefore, be made as uncomplicated as possible while still allowing safe separation from the other elements of the flight. Maintaining a specified altitude and heading away from the flight until further notice is an ideal lost wingman procedure, in that it avoids frequent or prolonged disorientation-inducing turns and minimizes cognitive workload. Often a pilot flying wing in bad weather does not lose sight of the lead aircraft, but suffers so much disorientation stress as to make the option of going lost wingman seem safer than that of continuing in the formation. A common practice in this situation is for the wingman to take the lead position in the formation, at least until the disorientation disappears. This avoids the necessity of having the disoriented pilot make a turn away from the flight to go lost wingman, which could be especially difficult and dangerous because of his disorientation. One should question the wisdom of having a disoriented pilot leading a flight, however; and some experts in the field of spatial disorientation are adamantly opposed to this practice, with good reason.

Verbal communication between pilots can help prevent disorientation. In formation flight in weather, for example, it is good practice for the flight leader to inform his wingman periodically of the attitude, altitude, airspeed and heading of the flight, as the task of formation flying makes it difficult for the wingman to obtain accurate orientation information by monitoring flight instruments. In some cases a copilot or other crew member is available to monitor aircraft attitude, motion, and position during times when the pilot is fully occupied with other demanding tasks (e.g., weapons delivery at night). The other crew member's verbal orientational status reports or warnings of hazardous orientations can serve the pilot well under such circumstances.

The manner in which others communicate with the pilot who is disoriented can mean the difference between life and death for that pilot and his passengers. Unfortunately, no clear-cut procedure exists for ensuring appropriate communications to a disoriented pilot. Should he be hounded mercilessly with verbal orders to get on the instruments, or should he be left relatively undistracted to solve his orientation problems? The extremes of harassment and neglect are definitely not appropriate; a few forceful, specific, action-oriented commands probably represent the best approach. "Level the artificial horizon!" and "Roll right 90 degrees!" are examples of such commands. One must remember that the pilot suffering from spatial disorientation may be either so busy or so functionally compromised that friendly chit-chat or complex instructions may fall on deaf ears. Simple, emphatic directions may be the only means of penetrating the disoriented pilot's consciousness.

To illustrate how official recommendations regarding inflight procedures are disseminated to pilots in an effort to prevent spatial disorientation mishaps, a message from a major United States Air Force command headquarters to field units is excerpted here:

> "...Review SD procedures in [various Air Force manuals]... Discuss the potential for SD during flight briefings prior to flight involving night, weather, or conditions where visibility is significantly reduced... Recognize the [SD] problem early and initiate corrective actions before aircraft control is compromised.
>
> A. Single Ship:
>
> (1) Keep the head in the cockpit. Concentrate on flying basic instruments with frequent reference to the attitude indicator. Defer non-essential cockpit chores.

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(2) If symptoms persist, bring aircraft to straight and level flight using the attitude indicator. Maintain straight and level flight, until symptoms abate--usually 30 to 60 seconds. Use autopilot if necessary.

(3) If necessary, declare an emergency and advise air traffic control. Note: it is possible for SD to proceed to the point where the pilot is unable to see, interpret, or process information from the flight instruments. Aircraft control in such a situation is impossible. A pilot must recognize when physiological/psychological limits have been exceeded and be prepared to abandon the aircraft.

B. Formation flights:

(1) Separate aircraft from the formation under controlled conditions if the weather encountered is either too dense or turbulent to insure safe flight.

(2) A flight lead with SD will advise his wingmen that he has SD and he will comply with procedures in Paragraph A. If possible, wingmen should confirm straight and level attitude and provide verbal feedback to lead. If symptoms do not abate in a reasonable time, terminate the mission and recover the flight by the simplest and safest means possible.

(3) Two-ship formation. Wingman will advise lead when he experiences significant SD symptoms.

(a) Lead will advise wingman of aircraft attitude, altitude, heading, and airspeed.

(b) The wingman will advise lead if problems persist. If so, lead will establish straight and level flight for at least 30 to 60 seconds.

(c) If the above procedures are not effective, lead should transfer the flight lead position to the wingman <u>while in straight and level flight</u>. Once assuming lead, maintain straight and level flight for 60 seconds. If necessary, terminate the mission and

> recover by the simplest and safest means possible.
>
> (4) More than two-ship formation. Lead should separate the flight into elements to more effectively handle a wingman with persistent SD symptoms. Establish straight and level flight. The element with the SD pilot will remain straight and level while other element separates from the flight."

Cockpit Layout and Flight Instruments. One of the most notorious vertigo traps is the communications-transceiver frequency selector or transponder code selector located in an obscure part of the cockpit: to manipulate this selector requires the pilot not only to look away from his flight instruments, thus interrupting his instrument scan, but also to tilt his head to view the readout, thus potentially subjecting him to a Coriolis or G-excess illusion. Aircraft designers are now aware that easy accessibility and viewing of such frequently used devices minimize the potential for spatial disorientation; accordingly, most modern aircraft have communications frequency and transponder code selectors and readouts located in front of the pilot near the flight instruments.

The location of the flight instruments themselves is also very important: they should be clustered directly in front of the pilot, and the attitude indicator--the primary provider of orientation cueing and the primary instrument by which the aircraft is controlled--should be in the center of the cluster (Fig. 26). When this principle is not respected, the potential for spatial disorientation is increased. A certain modern fighter aircraft, for example, was designed to have the pilot sitting high in the cockpit to enhance his field of view during air-to-air combat in conditions of good visibility. This design relegated the attitude indicator to a position more or less between the pilot's knees. As a result, at night and during instrument weather, the pilot is subjected to potentially disorienting peripheral visual motion and position cueing by virtue of his being surrounded by a vast expanse of canopy, while he tries to glean with central vision the correct orientation information from a relatively small, distant attitude indicator. The net effect is an unusually difficult orientation problem for the pilot, and a greater risk of developing spatial disorientation in this aircraft than in others with a larger and more advantageously located attitude indicator.

The verisimilitude of the flight instruments is also a major factor in their ability to convey readily assimilable

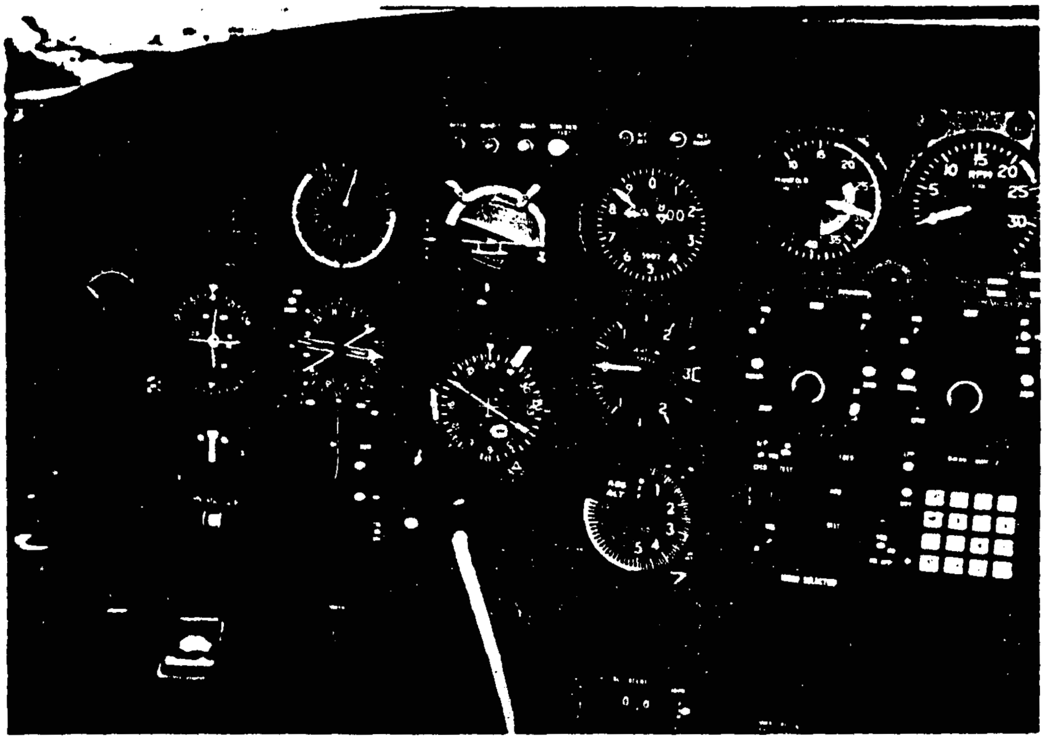

Figure 26. A well-designed instrument panel, with the attitude indicator located directly in front of the pilot, and the other flight instruments clustered around it. Radios and other equipment requiring frequent manipulation and viewing are placed close to the flight instruments to minimize interruption of the pilot's instrument scan and to obviate his having to make head movements that could precipitate spatial disorientation. (Photo courtesy of Gen-Aero, Inc., San Antonio, TX.)

orientation information. The old "needle, ball, and airspeed" indicators (a needle pointer showing the direction and rate of turn, a ball showing whether the turn is being properly coordinated with the rudders, and an airspeed indicator showing whether the airplane is climbing or diving) required a lot of interpretation for the pilot to perceive his spatial orientation through them; nevertheless, this combination sufficed for nearly a generation of pilots. When the attitude indicator (also known as the gyro horizon, artificial horizon, or attitude gyro) was introduced, it greatly reduced the amount of work required to spatially orient during instrument flying because the pilot could readily imagine the artificial horizon line to be the real horizon. In addition to becoming more reliable and more versatile over the years, it became even easier to interpret: the face was divided into a gray or blue "sky" half and a black or brown "ground" half, with some models even having lines of perspective converging to a vanishing point in the lower half. Such a high degree of similarity to the real world has made the attitude indicator the mainstay of instrument flying today.

A relatively new concept in flight instrumentation, the head-up display (HUD), projects numeric and other symbolic information to the pilot from a combining glass near the windscreen, so he can be looking forward out of the cockpit and simultaneously monitoring flight and weapons data. When the pilot selects the appropriate display mode, pitch and roll attitude of the aircraft are observed on the "pitch ladder" (Fig. 27) and heading, altitude, airspeed, and other flight parameters are numerically displayed elsewhere on the HUD. Its up-front location and its close-together arrangement of most of the required aircraft control and performance data make the HUD an attractive alternative to the conventional cluster of instruments, and some pilots use the HUD as the primary instrument for spatial orientation and aircraft control during instrument flight. Pilots' acceptance and use of the HUD for flying in instrument weather has not been universal, however: many prefer to use the HUD under conditions of good outside visibility and use the conventional instruments for flying at night and in weather. The reason for this preference may be that the horizon on the conventional instrument looks more like the natural horizon than does the zero-pitch indicator on the HUD pitch ladder. Another reason may be that the HUD presents such a narrow view of the outside world--a "vernier" view with high resolution--while the conventional attitude indicator gives an expansive pictorial view of the spatial environment. Furthermore, the relative instability of the HUD pitch ladder and the tendency for the zero-pitch line to disappear from view make the HUD somewhat difficult to use during moderately active maneuvering, as would be necessary during an unusual-attitude recovery attempt.

As good as they are, both the attitude indicator and the HUD leave much to be desired as flight instruments for assuring spatial orientation. Both suffer from the basic design deficiency of presenting visual spatial orientation information to the wrong sensory system--the focal visual system. Two untoward effects result. First, the pilot's focal vision not only must serve to discriminate numerical data from a number of instruments, but also must take on the task of spatially orienting the pilot. The pilot thus has to employ his focal visual system in a somewhat inefficient manner during instrument flight, with about 70% of his time spent viewing the attitude indicator, while his ambient vision remains unutilized. Second, the fact

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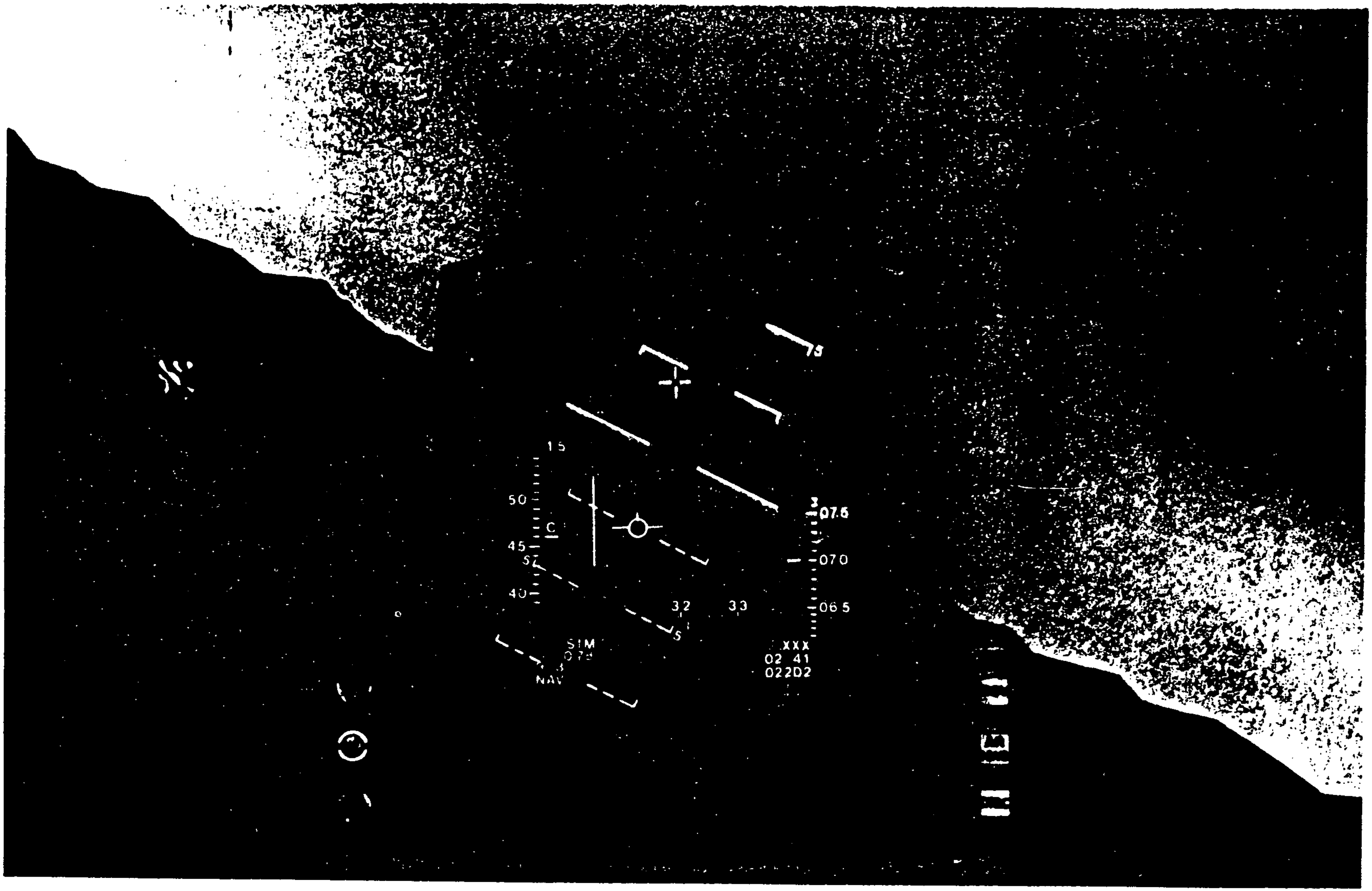

Figure 27. A typical head-up display (HUD). The pitch ladder in the center of the display provides pitch and roll attitude information.

that focal vision is not naturally equipped to provide primary spatial orientation cues causes pilots difficulty in interpreting the artificial horizon directly: there is a tendency, especially among novice pilots, to sense backwards the displayed deviations in roll and pitch, and to make initial roll and pitch corrections in the wrong direction. Several approaches have been taken to try to improve the efficiency of the pilot's acquisition of orientation information from the attitude indicator and associated flight instruments. One has been to make the artificial horizon stationary but to roll and pitch the small aircraft on the instrument to indicate the motion of the real aircraft (the so-called "outside-in" presentation, as opposed to the "inside-out" presentation of conventional attitude indicators). Theoretically, this configuration relieves the pilot of having to spatially orient himself before trying to fly the aircraft: the pilot merely flies the small aircraft on the attitude instrument and the real aircraft follows, so to speak. This approach, however, fails to free foveal vision from the unnatural task of processing spatial orientation information. Another concept, the peripheral visual horizon display (PVHD), also known as the Malcolm horizon, attempts to give pitch and roll cues to the pilot through his paracentral and peripheral vision, thereby sparing foveal vision for tasks requiring a high degree of visual discrimination.[25,26] The several varieties of PVHD that have been developed project across the instrument panel a long, thin line of light representing the true horizon, which line of light moves directly in accordance with the relative movement of the true horizon (Fig. 28). The potential for further development and eventual pilot acceptance of PVHD-type aircraft attitude displays appears good, as the PVHD is based on the physiologically sound concept of providing primary spatial orientation cueing through ambient vision--i.e., in the natural fashion.

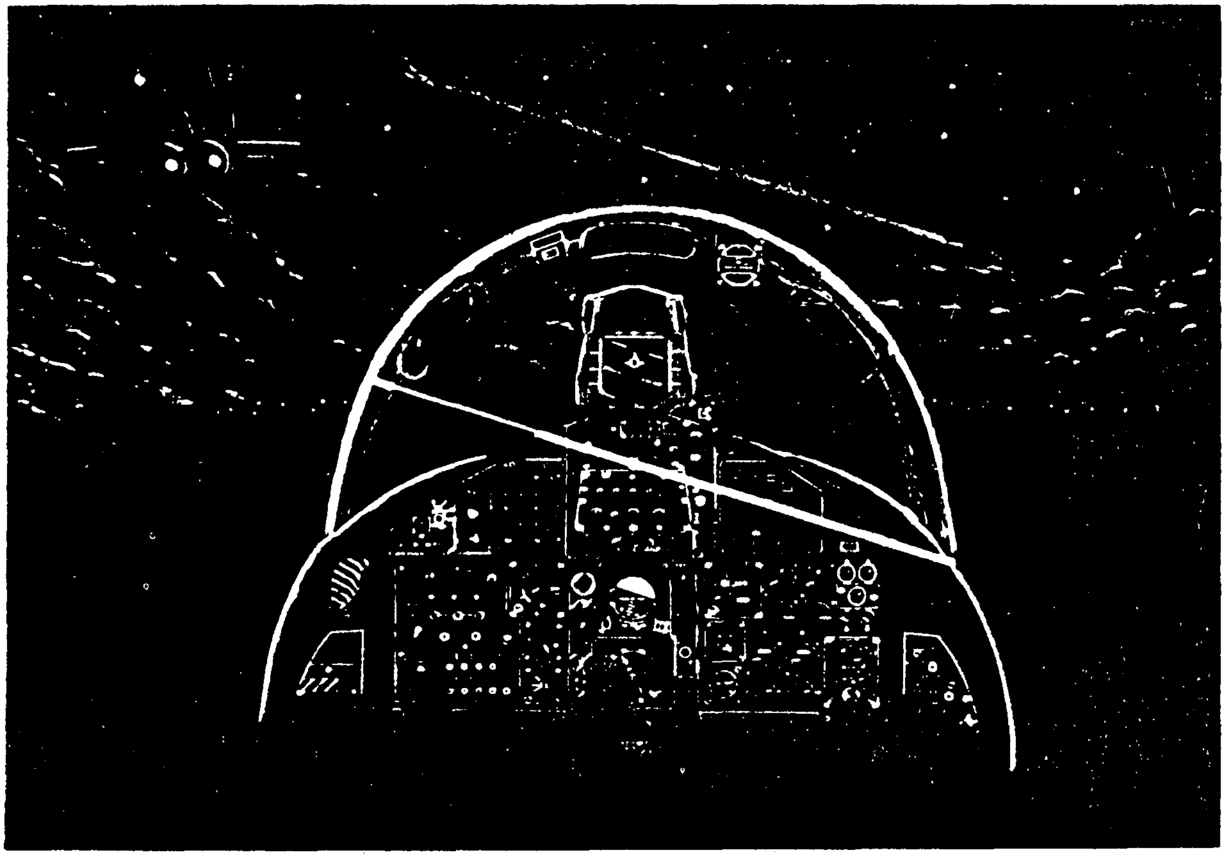

Figure 28. The peripheral visual horizon display (PVHD), or Malcolm horizon. An artificial horizon projected across the instrument panel moves in accordance with the real horizon, and the pilot observes the projected horizon and its movement with his peripheral vision. Theoretically, this enables him to process spatial orientation information in the natural fashion, and spares his foveal vision for tasks requiring a high degree of visual discrimination.

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INTEGRATING THE HUMAN INTO THE DESIGN PROCESS: A CRITICAL CHALLENGE WHOSE TIME HAS COME

David W. Milam, Colonel, USAF

BIOGRAPHY

Colonel David W. Milam is the Deputy System Program Director for B-1B, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson AFB, OH.

Colonel Milam was born on July 12, 1940 in Tuscon, AZ and graduated from Central High School in Pueblo, CO in 1958. After attending Pueblo Junior College for one year, he went to the USAF Academy where he graduated in 1963. He received a Master of Sciences degree in Aeronautical Engineering from the University of Arizona in 1971. Colonel Milam attended the USAF Test Pilot School in 1973. He is a 1977 graduate of the Armed Forces Staff College and a 1983 graduate of the Air War College.

Upon receiving his commission from USAFA, he attended pilot training at Moody AFB, GA and graduated in September of 1964. After graduation, he attended F-100 RTU at Luke AFB, AZ and was subsequently assigned to the 55th TAC Fighter Squadron at RAF Wethersfield, England from June 1965 to June 1968.

From July 1968 to December 1968, he was a flight commander and maintenance officer at Bien Hoa AFB, Republic of Viet Nam. From January 1969 to July 1969, he was a briefing officer for the Commander of 7th Air Force at Ton Son Nhut AB, Republic of Viet Nam while continuing to fly F-100's at Bien Hoa.

Returning to the United States, he went to graduate school at the University of Arizona. After graduation, he was assigned to the Mechanics Department at the US Military Academy, West Point, NY from June 1971 to December 1972. He taught thermodynamics, fluid mechanics, and flight mechanics.

In January 1973, he entered the USAF Test Pilot School. After graduation in December 1973, he went to flight test operations where he managed several flight test programs on the F-4 and A-7. These test programs included flight control system improvements and advanced gunsights. He returned to the Test Pilot School in 1975 and taught flying qualities and linear control systems.

After graduation from the Armed Forces Staff College in May 1977, he returned to flight test operations at the Air Force Flight Test Center, Edwards AFB, CA. In October of 1978, he joined the F-16 Combined Test Force. He held numerous positions including program manager, operations officer, deputy director, and director. He accomplished many of the flight tests for flight control system development, gunsight development and out-of-control flight. During this period, he was also the Director of the AFTI/F-16 Joint Test Force. He was responsible for the initial formation of the joint test force and participated in the development of the AFTI/F-16 flight control system and cockpit controls and displays.

After graduating from the Air War College in May of 1983, he was assigned to the Air Staff as Chief of the Special Projects Division under the Director of Operational Requirements, Deputy of Research, Development and Acquisition. He managed a broad breadth of programs to include several programs in electronic warfare. He assumed his present duties in February 1986.

Colonel Milam is a command pilot with more than 3600 flying hours. His military decorations include Legion of Merit with one oak leaf cluster, Distinguished Flying Cross, bronze star, Meritorious Service Medal, Air Medal with seven oak leaf clusters, Air Force Commendation Medal with three oak leaf clusters, Presidential Unit Citation emblem and Air Force Outstanding Unit Award with five oak clusters and valor device.

INTRODUCTION

In my nine years as a test pilot at the Air Force Flight Test Center (AFFTC) I have been involved in some great successes and some expensive failures. I have seen two different pilots get into a Pilot-Induced Oscillation (PIO) in the F-4; one aircraft was destroyed and the other was severely damaged. In both cases, there was nothing mechanically wrong with the aircraft. I have watched a landing PIO on the Space Shuttle at Edwards AFB and at Holloman AFB. I personally witnessed the inadvertant first flight of the F-16 when an experienced test pilot got into a lateral PIO on a high speed taxi check. I was the project manager on the F-16 gunsight when we discovered that a new gunsight was unstable when the pilot aggressively attempted to track a target; we didn't make that discovery until the gunsight had already been on the airplane for three years. All of these incidents were linked by a common element--human interaction with a machine. All of the machines had been carefully designed and thoroughly tested by experienced engineers and test pilots - yet the incidents still occured. Recent professional symposia indicate a growing interest and belief that important benefits can be obtained by insuring that the development of new aircraft be accomplished with a full understanding of the effect of the human on that aircraft.

The objective of any aircraft development program should be to optimize the total aircraft system which includes both the pilot and the vehicle. There are numerous, time-proven, well-known analysis techniques which can be used to predict aircraft response without the pilot in the loop. These techniques, such as Bode and root locus, allow limited analysis of the total system, i.e. pilot in the loop. Although these analysis techniques provide an effective tool for development of new flying qualities they have the limitation that they do not include the variable of pilot dynamics. In order to include the pilot in the design process, ground simulation must be accomplished. However, understanding the results of simulation requires that designers have an understanding of how humans accomplish motor skill tasks. Specifically, designers must understand human mental processes and brain architecture in order to analyze the performance of skill tasks in the simulator. Simulation includes the human element at an early stage in the design process when changes are easily made; changes late in the design process are often eliminated because they are too costly. There are some limitations to each of the parts of the design process (concept, engineering analysis, ground simulation, inflight simulation, and flight test) but, collectively, they can be used very effectively in optimizing a total system design.

DEVELOPMENT PROCESS

Military objectives are the result of political objectives and the National interest. In order to fulfill military requirements, which result from military objectives, civilian and military leaders attempt to obtain an optimum balance of (1) Force Structure, (2) Readiness, (3) Modernization, and (4) Sustainability. Monetary constraints force choices about the amount of modernization vs. size of the force, the degree of readiness, and the amount of spares for sustained operations. An optimum balance of the four variables is difficult to define precisely. Broadly speaking developers and testers must provide leaders with accurate assessments of total system capability so the leaders can determine if the purchase of a new system outweighs the importance of increased force structure, increased readiness, of increased sustainability. Civilian and military leaders desire precise statements of total system capability, but this is difficult for the developer to determine. There are many reasons why the development of new systems is so complex. One difficulty involves the uncertainty inherent in continuously pushing the technological state-of-the-art. Another difficulty is the lack of centralized control resulting from the large number of people in the development/testing process.

The task of defining total system capability demands that the decision maker have knowledge of six basic factors:

- o Survivability
- o Reliability
- o Maintainability
- o Performance
- o Workload
- o Cost

Although they are not the only factors which define total system capability, they are the most significant. A production decision is rational and intelligent only if accurate assessments of these factors have been provided to the decision maker. Although the decision maker wants facts, some of the "facts" are difficult to test in any quantitative manner and are little more than best guesses. The relevancy and utility of the facts are a function of the quality and quantity of testing.

Cost, reliability, maintainability, and performance can all be measured quantitatively, however, survivability and workload cannot. Cost is firm the day a contract is signed, but it subsequently changes. Some sources of cost growth are: engineering changes throughout the development of a system, changes of production rate and quantity, schedule changes, initial estimate inaccuracies, unforseen problems, and changes in logistic support. Reliability can be estimated by reviewing the performance of hand-made test vehicles but only operational experience gives accurate numbers. Maintainability can also be measured on a test vehicle that is maintained by skilled aircraft technicians, but will certainly change when young enlisted people are working on the airplane at an operational base. Performance can be measured in many ways such as time to climb, turn rate, specific excess power (Ps), radar range, roll rate, etc., but these will change in the production vehicle because of design changes and system growth. The difficult decision is to determine how much weight to give to each of these performance parameters. Survivability is difficult to measure quantitatively because it depends on threat capabilities as well as friendly capability. There is the potential to estimate survivability with simulator studies but the simulation is based on many assumptions of number of weapons, alert status, tactics, etc. Pilot workload cannot be measured as precisely as the other basic factors. There are at lease three ways to measure workload:

- o clinical (non-intrusive) measure of pilot biological factors such as heart rate,
- o secondary task performance,
- o and pilot subjective opinion.

Although researchers have examined clinical methods of measuring pilot workload, they have not identified a precise way to enumerate changes in physical and mental workload. Severe limitations afflict the use of secondary task performance as workload indicators, because of the inability to create the actual flight conditions, such as stresses. Qualititive pilot opinion is still the best method to gather workload measurement.

Thus, civilian and military decision makers are placed in a quandry about the amount of weight to be given to each factor. If cost gets too high, it can be the dominant factor, but it might be a very small factor if the cost is reasonable. If the pilot workload is so high that it makes a system unuseable, then it might be the dominant factor. Unfortunately, the decision about the weight to give each factor is normally much more difficult than these simple examples.

Any discussion of the development process demands an understanding of "inner loop" and "outer loop" design. The outer loop is the loop which is provided by the pilot. The inner loop is the actual vehicle or system itself. Analysis of aircraft flying qualities provides an excellent definition of "inner-loop" and "outer-loop" response. One method of studying aircraft flying qualities involves preparing a series of equations which describe the system as sequential building blocks. For example, one equation describes the longitudinal aerodynamics of an airplane. That equation, used as one of the building blocks, is expressed by a LaPlace transform. Thus, for a specific elevator deflection (input) and specific flight condition the response (output) can be accurately predicted. (Fig 1):

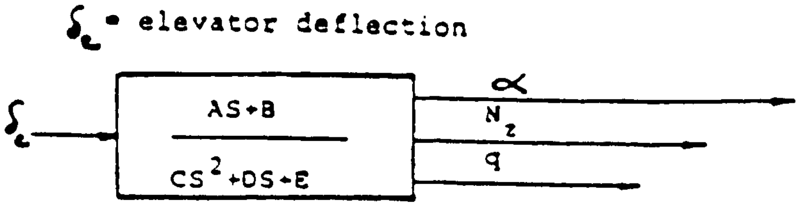


Figure 1. AERODYNAMIC BLOCK DIAGRAM

All of the appropriate parameters of longitudinal aircraft motion are specified but the parameters of greatest interest are angle of attack ( ), pitch rate (q), and load factor (Nz). In a like manner the flight control system can be modeled with control stick deflection as the input and elevator deflection as the output. (Fig 2):

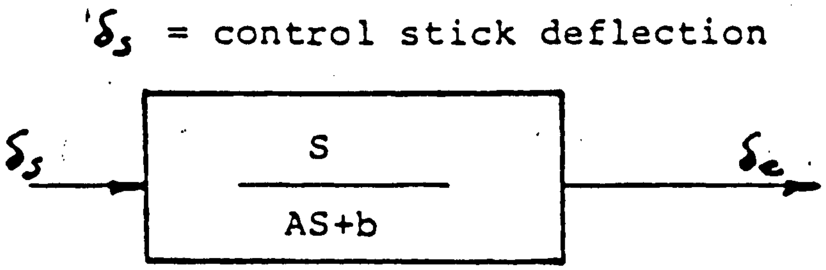


Figure 2. SERVO ACTUATOR BLOCK DIAGRAM

In any modern airplane most output signals feed back, modifying the input to provide additional control and stability augmentation. These feedback signals are modified by filtering and be gain changes. In addition, the pitch rate signal is normally "washed out" with time. A complete, simplified block diagram is thus developed. (Fig 3):

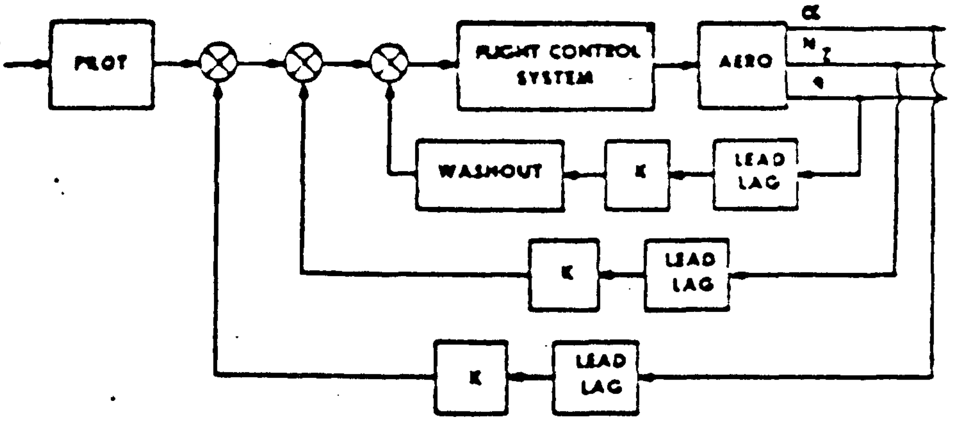


Figure 3. SIMPLIFIED INNER LOOP DIAGRAM

Because all of the parameters in each block are specified within acceptable limits, any engineer can analyze system response, making possible system response of the "inner-loop" diagram to standard inputs.

The pilot interface is not so easily defined. The pilot also senses angle of attack, load factor, and pitch rate, so he establishes an outer loop around the inner loop. (Fig 4):

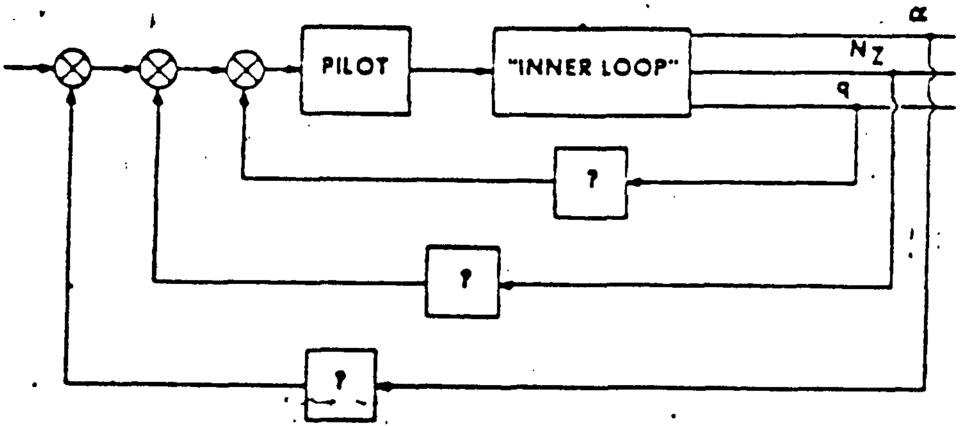


Figure 4. OUTER LOOP DIAGRAM

The characteristics of these "outer-loop" feedbacks are variable. They vary from pilot to pilot and from time to time. This added complexity prohibits simple analysis of the total system response. Ground and flight simulations offer some insights into the effect of this outer loop. The difficulty of "outer loop" or total system (i.e. pilot-in-the-loop) analysis is that pilots are unique; each pilot will react in a different manner to the same stimulus. In a properly structured test program there is a blend of inner-loop and outer-loop testing.

There are five development process steps which are essential because of the shortcomings of our present analytical capabilities:

- Concept - a new design or a modification
- Engineering Analysis - preliminary "inner-loop" analysis
- Ground Simulation - initial "outer-loop" analysis in a high fidelity ground simulator
- Inflight Simulation - additional "outer-loop" analysis in an inflight simulator
- Inflight test - actual vehicle or modification flight test

The development process is an iterative process of design, testing, redesign, testing, redesign, etc. (Fig 5):

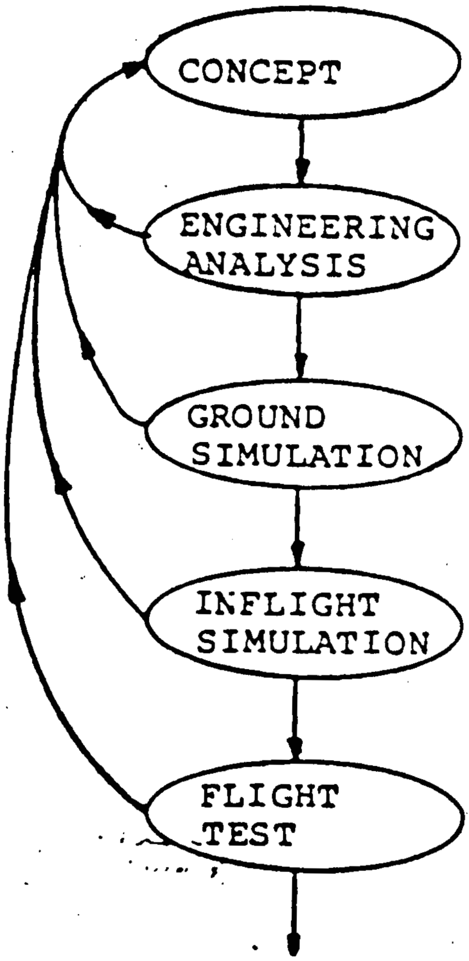


Figure 5. DEVELOPMENT PROCESS

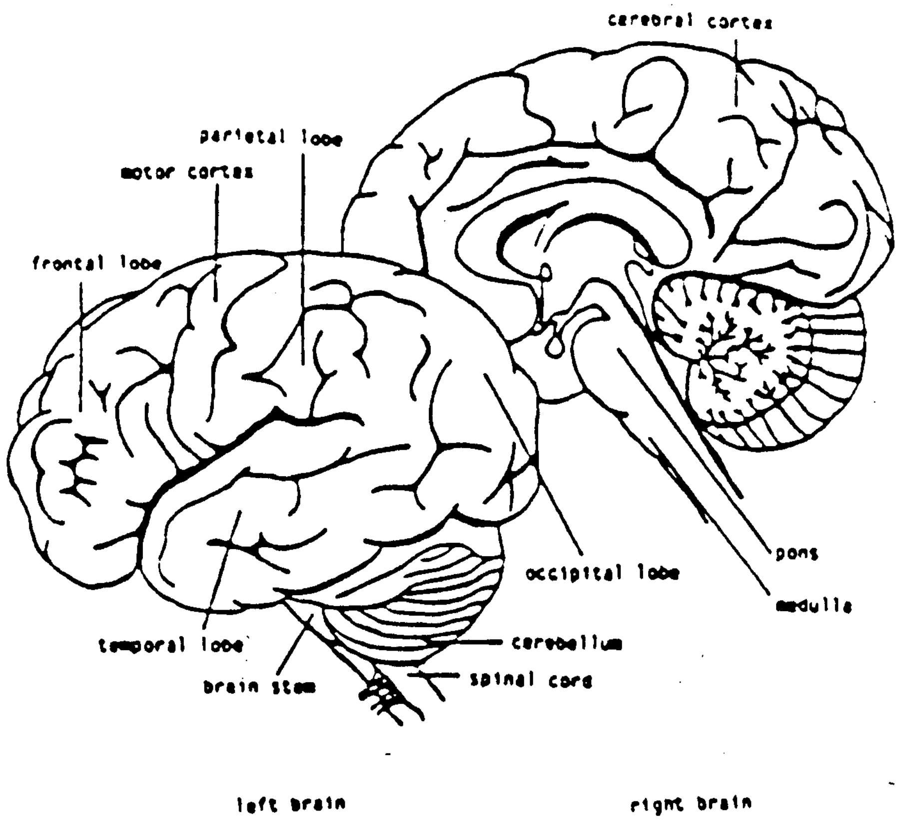


Figure 6. ARCHITECTURE OF THE BRAIN

In many programs, simulation is either not undertaken, or is undertaken too late in the design process to be effective in identifying problems because large retrofit costs prevent changes late in the development process. If any of these five essential steps are eliminated, the probability for mistakes increases greatly. Each step has limitations, but the total process allows the design to mature and be optimized for interface with the human operator. It is the last three that provide the opportunity for pilot-in-the-loop analysis.

MENTAL PROCESS

As a part of the development process, aircraft developers assess both workload and performance. Both of these require "outer-loop" analysis. That analysis demands use of simulation and flight test. When simulation and flight test are finished, data interpretation is complicated by the uncertainty in how humans do skill tasks. Therefore, in order to use simulator results in an educated way, developers and testers must understand how humans do skill tasks. There is a large gap between the laboratory (academic world) and the aircraft design world on how humans do motor skill tasks. Aircraft design can be optimized for the human operator only if that gap is closed; aircraft design must be accomplished with a thorough understanding of how the human operator (pilot) accomplishes motor skill tasks. Research in psychology can yield some valuable results in pilot performance.

Brain Architecture

The brain is an extremely complicated mechanism and science is just beginning to understand all of its functions. (Fig. 6)

The brain stem rises from the top of the spinal cord. In the brain stem are two structures that together control breathing itself: one is the medulla and the other is the pons. Breathing is a prime example of a behavior that is prewired in the brain. It does not have to be learned, or even consciously willed, but continues semi-automatically. In front of the brain stem is the pituitary gland which hangs from a stalk like a tiny fruit. It serves as one of the main regulators of body chemistry and so powerfully affect behavior that it is considered part of the brain. Perched on the highest rear branch of the brain stem is the cerebellum. It maintains the body's equilibrium and coordinates muscles during fine movements. The brain stem and its associated structures are practically hidden by two connected bodies, the cerebral hemispheres.

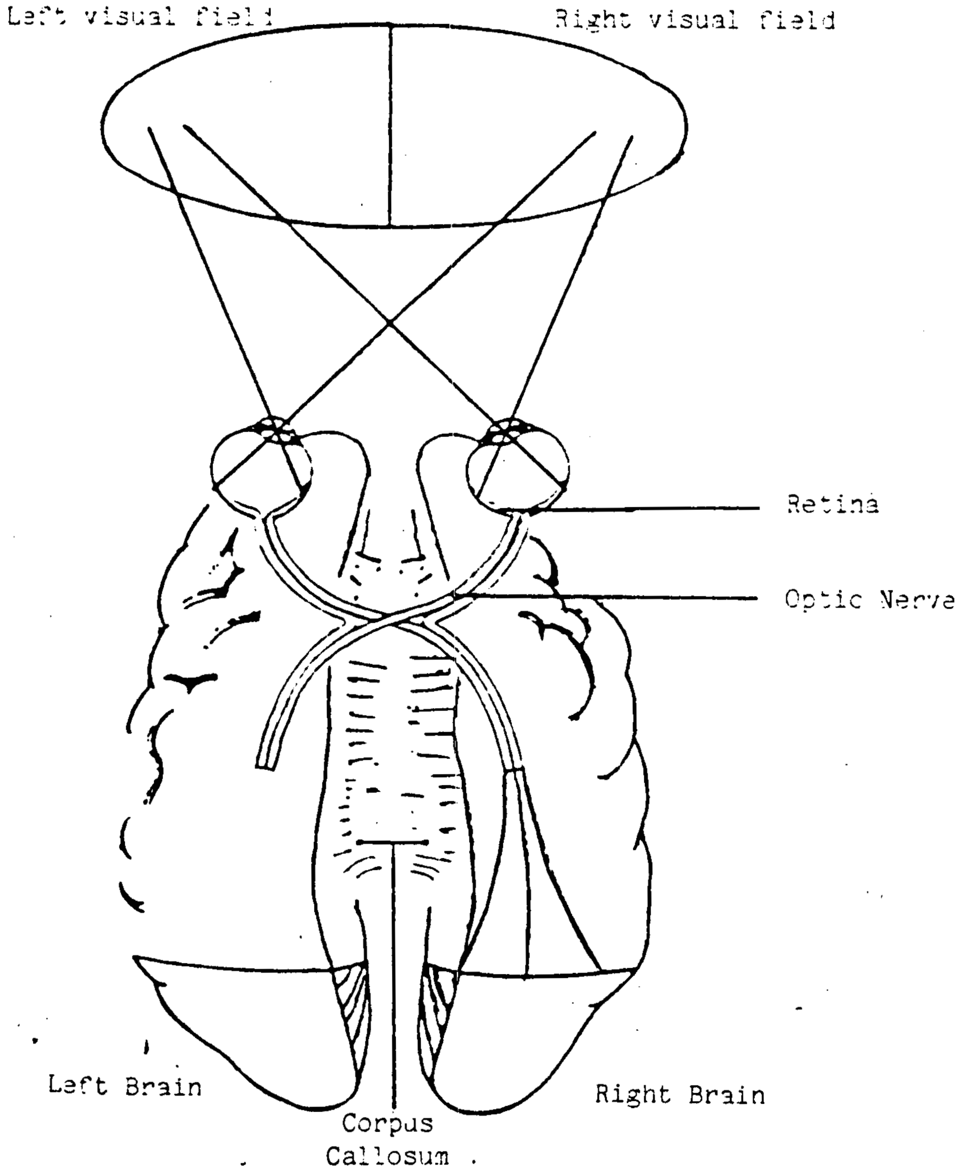
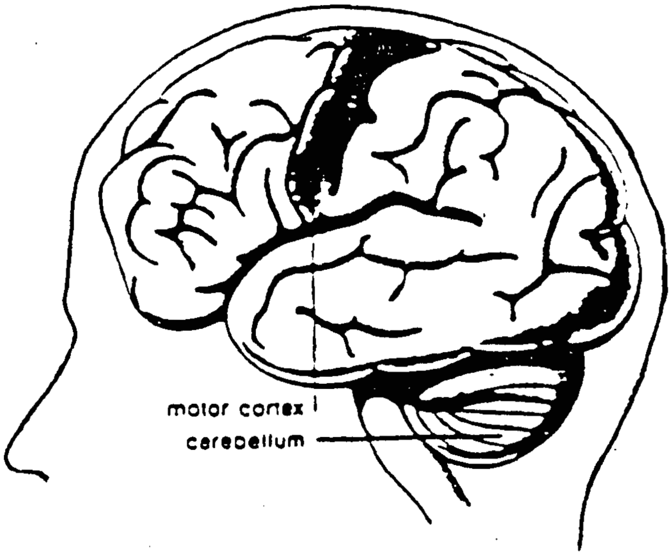


Figure 7. CEREBRAL HEMISPHERES

(Fig. 7): The thalamus, at the core of the hemispheres, is the control switchboard between the spinal cord and the brain's upper levels. The hypothalamus is a complex center of emotions and drives; it lies below the thalamus, commanding the body's responses to stress. It sets off instinctive behavior aimed at self preservation; for example, warning of hunger and thirst. It triggers sexual activity. Most dramatically, it generates intense feeling of anger, fear, and even pleasure. The cortex lies in the crumpled covering of the cerebral hemispheres. The cortex contains the centers responsible for man's uniqueness: the capacity for language, the delicate motor control that makes possible the use of tools, the safety devices that manage built-in drives and emotions, and the interpretive systems that enable man to perceive himself and the world around him. The cortical folds create a rugged topography of ridges and furrows. The furrows demarcate each hemisphere into four separate lobes: occipital lobe at the back of the head, parietal lobe, temporal lobe, and the frontal lobe. The back portion of the frontal lobe is the motor cortex which is the command center for voluntary movement and it is divided according to bodily topography.



A view of the left side of the brain shows the motor cortex running across the top of the brain. Muscular activity is coordinated by the cerebellum, at the bottom of the brain.

Figure 8. MOTOR CORTEX AND CEREBELLUM

(Fig. 8): Three-fourths of the cortical terrain is uncharted. Somewhere in the labyrinths of the cortex lies man's attributes of thought, creativity, and love. Automatic reflexes account for only a few of the body's nerve circuits. Most muscle movements are voluntary; the individual consciously controls them through tracts of nerve pathways that extend from the brain through all regions of the body. The main tract descends directly from the wrinkled gray matter at the very top of the brain, known as the motor cortex. Scientists have mapped the circuitry of the motor cortex with astonishing precision. The motor cortex does not control muscle movements all by itself. New techniques for probing beneath the surface of the brain have revealed that other command centers work in tandem with the motor cortex.

Coordinating movements is the province of the cerebellum. The cerebellum is wired to the motor cortex, the basal ganglia, and to sensory apparatus: eyes, ears, and especially the long nerves that alert the brain to every movement a muscle makes; for example when a person reaches out to shake hands with a friend, the cerebellum computes the relative position of the two hands and automatically guides the hand and adjusts its speed for a smooth greeting. Of all the behavioral command centers, only the cerebellum has circuits so straight-forward in their connections that scientists have traced in them what an electronics engineer would recognize as a wiring diagram. The neurons are arranged in precise patterns that repeat themselves over and over again like printed circuits in a computer. The cerebellum is a recording machine that tapes muscular actions involved in a complex and habitually used movement and then plays back entire sequences on command.

In trying out new skills for the first time, a person tends to think through and consciously order each movement, a process which presumably takes place in the higher brain centers. These consciously thought-out commands are fed through the cerebellum; its circuits perceive the higher cerebral activity and instantaneously reproduce it, like the ballet student who mimics the steps his teacher is demonstrating. In time the cerebellar circuits no longer have to watch; they take over the precise coordination of the skilled movements, so that the individual need not bother to think about the details anymore. Thereafter, nerve cells in the motor cortex can simply switch on the cerebellum's play-back mechanism and get the same result--much as pushing the button on a tape recorder plays back a song.

Skill Task Performance

Based on the discussion of brain architecture, a general discussion of motor skill tasks in sports provides a good foundation prior to discussing specific flying skill tasks. Performance of skill tasks in flight closely parallels that of sports skill tasks such as tennis, basketball, skiing, or riding a bicycle. Most of the mental work in all of these tasks is done on a subconscious level. The subconscious work is done in one part of the brain (cerebellum) and the conscious work is done in another part (motor cortex). The foveal vision of the eye (the central vision or sharply focused vision) is processed by the conscious part of the brain. The subconscious part of the brain processes both the foveal and peripheral vision. The conscious part of the brain performs the reasoning or analytical functions and it only does one thing at a time. In essence it "time shares" various tasks and problems and takes some finite amount of time to accomplish each separate calculation, decision, or analysis. The subconscious mind, on the other hand, responds to information and gives out a large number of commands simultaneously; it can do many different functions at the same time. With these thoughts in mind, it is obvious that the key to all skill tasks is to do most of the work on the subconscious level. In each separate skill task, the person must use the correct visual reference and then accomplish a large amount of practice to establish a large data base in the subconscious mind. That practice process can be referred to as "programming core" because of the obvious similarity with digital computers. As previously discussed, the subconscious mind (cerebellum) has such a good tape that all of the specific tasks can be accomplished without monitoring or control from the conscious mind. Every individual can recall driving a car down a highway for a considerable distance while the conscious mind was occupied in daydreaming or conversation on an unrelated subject.

That learning process of skill tasks has also been described in slightly different works although the basic philosophy is the same. Learning a skill involves three stages:

- Structuring (knowledge of basic principles)
- Accretion (acquisition of actual facts and structures of the skill)
- Tuning (acquiring automatic performance through repeated practice and utilization)

In each separate skill task the sighting reference is critical. Firstly, because of the strong tie between foveal vision and the conscious mind, the conscious mind becomes occupied when the individual concentrates on the sighting reference and that allows the subconscious mind to do most of the task. Secondly, in every skill task the brain needs some visual reference as a foundation from which to make adjustments. In tennis, the great player watches the ball so intently that he can actually see the seams. In basketball, the great player with the consistent jump shot always focuses instinctively on some specific part of the basket. The great hitters in baseball watch the ball so intently that they can actually see the spin of the ball.

It is imperative that the majority of mental work be on a subconscious level: When the individual elevates parts of a task to the conscious level, he invariably slows down in his performance as exemplified by typists and pianists. as well as in sports. An outstanding player is an individual who has supreme confidence in himself and in his coach so that he leaves most of the task on the subconscious level. If the coach tells him to do something in a specific way, then he practices until he has "programmed" the specific parts of the task on the subconscious level. When this individual is asked how he does a task, he tends to answer by saying that he does what comes naturally ("do whatever it takes"). There are some good players who try to dig into all the separate parts of a task, and by doing this, they elevate each part of the task to the conscious level. They can attain some high performance level but they never quite become the greatest. They are just a little bit slower than the "natural athlete" which was described first. This second individual becomes the really great coach even though he was never the best of his field as a player. This fact is logical because the natural athlete never did study the intricacies of a task while the good coach has studied each task in exhaustive, thorough, comprehensive detail and can, therefore, teach others. By elevating the task to the conscious level, he understood it better, but he also prevented himself from being absolutely great. When a coach who has studied tasks in detail teaches his players, he speaks from a sound foundation in fundamentals and urges them to master the proper skills. As his advice leads them to success, the players gain confidence in themselves and their coach and, subsequently leave most skill tasks on the subconscious level. From this confidence in the coach, team, and self, athletic winning traditions are established. Teams win because they think they will win; teams lose because they think they will lose. As stated in a book titled Maximum Performance "Think when you need to, and do when you need to, but make it a rule to keep your thinking and doing separate."

In all of these skill tasks it is very important that the mind and the body be in tune. The inner self and outer self must be in harmony; Both the physical self and the mental self must be relaxed but alert.

Specific Flying Skill Tasks

Just as in all sports, there are parts of the flying task which require skill while some things involve brute force. A pilot must use all of the cues available and he must have a good visual cue. When landing an airplane or accomplishing air to air tracking, the pilot must practice those tasks several times to "program core." The conscious mind "time shares" its tasks; therefore, it becomes important to establish some priority of things that need to be consciously monitored or checked. Hence the standard instrument cross check becomes very important to flying good instruments. Checking two or more instruments requires rapid switching between the different instruments. The conscious mind/foveal vision spend most of its time on the primary visual cue (attitude indicator). Other parameters are reviewed on a time-sharing basis: altitude, airspeed, position, engine parameters, vertical velocity, etc. Conscious and subconscious tasks are occuring simultaneously; the checking of individual aircraft instruments is a series of conscious level tasks while the actual moving of the stick is a subconscious task. The human is a serial processor for cognitive (conscious) level tasks, so the conscious level tasks must be organized into an efficient pattern or sequence. A good instrument pilot has a highly organized, methodical instrument cross check. The check becomes (Fig 9):

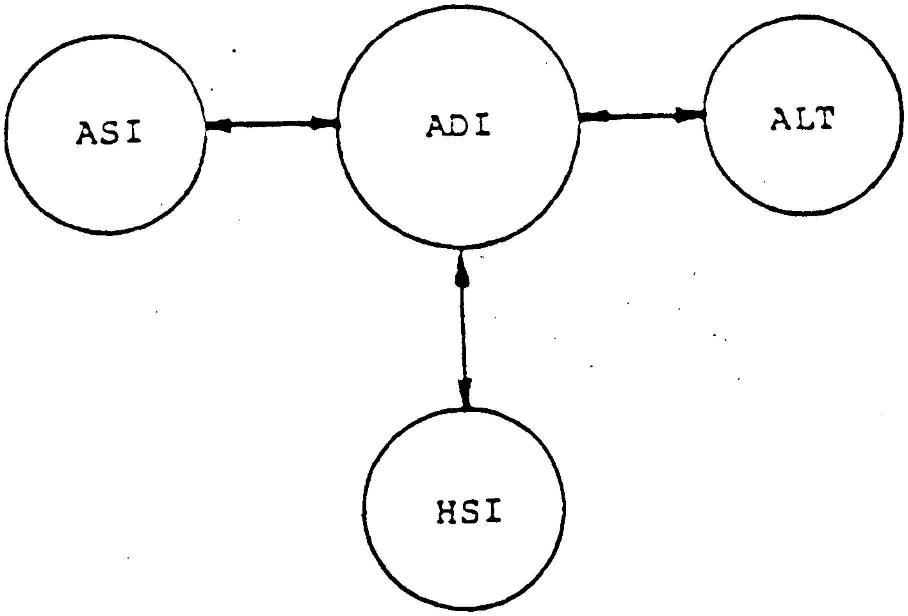


Figure 9. STANDARD INSTRUMENT CROSS CHECK

The key to air-to-air gunnery is also obvious. Eyes focus primarily on the target. The subconscious mind does most of the work. "Time share" the conscious level tasks in the proper sequence: radar lock-on, getting in the target's turning plane, starting the pipper drifting towards the target, accomplishing fine tracking, and shooting at the right time. The pilot should be physically and mentally relaxed but alert. If he believes he can hit the target, he will hit the target. Of course, all of this assumes that the gunsight is accurate. The development community needs to have a deep understanding of how the pilot does the skill task of air to air gunnery in order to both buy and train better. The Air Force needs to purchase equipment that can guarantee a high probability of a kill, and then provide adequate crew training so that the pilot can "program core." One or two shots per year at a towed target is inadequate to yield a highly capable "gunslinger".

There are times when all of these facts will help the pilot to fly an airplane better but it may not kill him if he forgets them. At other times however, pilots place themselves in situations where the the smallest mistake can kill them: air to ground gunnery, air to air combat, or aerial demonstrations. In a demonstration, the pilot is flying extremely close to the ground and a mistake might kill him; it becomes very important to determine what parameters will kill him and what parameters will simply make the demonstration look a little less impressive. For each maneuver, the pilot must establish a priority list of parameters that need to be checked. Most of the flying task has been given to the subconscious mind while the conscious mind focuses on the correct sighting reference (aircraft attitude primarily) and time-shares checking other parameters based on the priority list established before flight. If the pilot "programs core" by practicing the demonstration several times, the demonstration can be made very safe. The same statements can be made about air to ground gunnery or air to air combat.

There can be many distractions which disturb the established routine. Anything that is external to the normal thought process may get elevated to the conscious level because "core" doesn't know what to do about this "unprogrammed event". Remember that the conscious mind does only one thing at a time (it "time shares" separate tasks) and that the normal parameter check sequence can be broken by an unprogrammed event. If one of those parameters that the pilot misses because of the disturbance is a critical parameter, then that disturbance might kill him.

In addition to external distractions, there are internal distractions. If the mind is occupied with something other than flying the airplane, then the pilot might miss a critical parameter. It is extremely important to cleanse the mind of all distractions. Most pilots will do this by going into isolation for a period of time prior to their demonstration. By mentally reviewing each maneuver and mentally flying the demonstration, then the pilot can cleanse his mind of other events which might cause a fatal distraction. All demonstration pilots should instruct their support crew and friends about the effect of a mental distraction. The ground crew should not bring problems to the pilot when he is in his airshow preparation. The pilot should know the possible fatal impact of mental distractions and should cleanse his mind of any last minute problems before he goes to fly the airshow. For example, any demonstration pilot is "tickling the bear" if he stays in the hospitality suite until just before his flight. Such overconfidence leads to filling the conscious mind with unneeded thoughts to the exclusion of safety critical cross checks. Many demonstration fatalities could have been avoided by following this checklist:

1. Prepare the demonstration and establish a parameter priority list for each maneuver.

2. Practice until "core" has been adequately "programmed" to give a safe demonstration. Do not change the show at the last minute without practice.

3. Go into isolation before the demonstration to cleanse the mind of extraneous distractions.

4. Get both the inner self and the outer self (mental and physical) relaxed but alert.

5. Do not allow external or internal distractions to disturb the conscious mind in its established parameter check sequence. The "unprogrammed event" can be a killer.

Thus, in summation, human skill tasks are learned through a process which seems to be consistent whether the skill task is flying an airplane or hitting a baseball. Several aspects of this process are:

1. <u>The mind works on two levels: conscious and subconscious</u>: The conscious mind does only one task at time while the subconscious mind accomplishes many tasks simultaneously. The conscious mind time shares. Every event which happens to you is stored in the subconscious. Skill tasks are accomplished best when the task is done at the subconscious level.

2. <u>Tie between Foveal vision and conscious</u>: The strong tie between foveal vision and the conscious mind is important because it establishes the necessity to have a good visual cue in each skill task: "watch the ball", "watch the rim", "stare at the target". Subconscious hand-eye coordination is developed in this way.

3. <u>Proper visual cue and practice is the key to skill task performance</u>: The key to skill task performance is to use the proper visual cue(s) and then to practice a great deal to get a good data base in the subconscious mind ("program core"). Of all the cues that are used to accomplish a skill task, the visual cue is by far the most important. Probably 90 percent of all cues for doing skill tasks are visual cues.

4. <u>Each pilot has a unique style</u>: It is extremely important to understand that each pilot is unique. Traditionally, we have tended to look for the standard pilot or the great pilot. He doesn't exist. "The world's greatest fighter pilot" only exists at the Officers' Club Bar.

5. <u>Inner self and outer self must be in harmony</u>: The pilot's physical self and mental self must be relaxed but alert.

Impact of the Human on the Design Process

Based on an understanding of the design process and an understanding of the mental process for accomplishment of motor skill tasks, it is possible to assess the impact of the human on the design process. Two questions are obvious. What design considerations should be made in order to accommodate the human operator? What limitations on the design process arise from the human as a tester?

No two pilots are exactly alike. Although pilots display strong similarities in flying techniques, each pilot is unique. This consideration leads to four conclusions:

First, several pilots must be used for any evaluation which attempts to make objective data out of subjective pilot opinion. Four pilots normally give an adequate cross section. Attempts to use more than eight pilots become cumbersome. Large numbers of pilots give more confidence in the results because of the large sample size, but the evaluation process becomes too lengthy, and it becomes difficult to get pure pilot opinion.

Second, there will be differences of opinion during any evaluation. This does not imply that one pilot is right and the other is wrong. It becomes necessary, then, to design flying qualities that no single pilot finds unacceptable. The flying qualities of the final "best" configuration are those that are most acceptable to the entire group. There is an old saying which is appropriate given the ambitious flight test schedules, cost overruns, and limited funds of the present day: "Better is the enemy of good enough." Evaluators must be conscientious but they cannot ignore the schedule and dollar constraints that are real problems to the System Program Office and the contractor. When the collective opinion says that a configuration is "good enough", then the testers have an obligation to stop trying to make it "better".

Third, the engineer has an almost impossible task trying to quantify subjective pilot opinion. In many cases, pilot opinion varies over the entire spectrum from fantastic to unsafe. This problem can be overcome in two ways:

- Define evaluation tasks so that all pilots are doing the same thing. This is not always successful because some pilots insist on doing things their own way. Other pilots do not do all assigned tasks because they find them difficult, or they feel that the task does not have any personal relevance.

- After flying each modification, all pilots meet to discuss their results. Pilots are asked to present and justify their ratings. Differences of opinion are resolved in a way that is clear to everyone. This would not happen if pilot ratings were simply given to the engineers. The communication of ideas in these meetings is very enlightening. Pilots need to do exactly the same task in order to allow meaningful comparison of pilot ratings. Even with these measures, there are misunderstandings because pilots are not talking about identical tasks. One pilot might be commenting on an approach while the other pilot is commenting on a landing.

Finally, the world to others is not the same as we see it. The objective is to design flying machines that are the optimum for everyone. We must pay particular attention when any pilot says that something is unusable or unsafe. We must also be deeply concerned whenever we encounter a wide range of pilot opinion. When this disparity occurs, the design under consideration is not optimum.

Since most of any skill task is accomplished on the subconscious level, special efforts will be required to obtain meaningful pilot opinions. Each pilot will have a different opinion so the optimum design will be the design that they all find acceptable. Because the skill task is accomplished primarily on the subconscious level, the pilots will not always be able to explain why they prefer one configuration over another. Some engineers will want to say that pilots do not know what they are talking about--the truth is that most non-flying engineers don't understand the human side of pilot/vehicle interface.

If a new piece of avionics equipment requires the pilot to interact with it on the conscious level, his workload has gone up. The increase in performance might justify the increase in workload. On the other hand, the increase in workload might prevent the pilot from using the equipment during high workload flight conditions because the conscious mind does only one thing at a time. When the pilot focuses his attention on a demanding function, such as locking onto an enemy target with the radar or analyzing information on the radar warning receiver, he may lose track of others. The conscious mind acts very rapidly, but is still "time shares". Cockpit design and avionics development require a good understanding of the human operator.

The requirement for high fidelity, ground simulation with an excellent visual scene is obvious. The visual scene should be wrap-around so that the pilot is provided both foveal and peripheral cues. Any major development program of a system which uses a human operator should have access to a high fidelity ground simulator. Simulation can also be a supplement to flight training in new, increasingly complex aircraft. Young crew members need to "program core" so that actions can be done quickly. Actual combat should not constitute their initial exposure to the threat.

CONCLUSION

In conclusion, it is obvious that the highly technical airplanes of today are limited by the performance capability of the pilot. The human has an immense potential to remember, analyze, and act, but he accomplishes skill tasks in a certain, specific pattern. The human pilot is a serial processor for cognitive thought and requires appreciable time for action. When trained properly, the human operator does most of the flying skill task on the subconscious level and he does many tasks simultaneously. The pilot has limitations in his ability to deal with unprogrammed events. To optimize the design of new systems, the engineer must consider the human in the development process. The aircraft industry is exploding with new ideas, such as:

- Flight in Six Independent Degrees of Freedom
- Unconventional Controls
- Multi-purpose Displays
- Voice Command
- Helmet-mounted Sight
- Integrated Fire and Flight Control
- Wide Field of View HUD
- Task-tailored Control Modes
- High 'g' Cockpit
- Sidekick Controllers

All of these new technologies must be evaluated and perfected. We need to communicate with the pilot in new and innovative ways such as voice and color, to name just two. We need to incorporate state estimators to determine when to display what piece of data. If the design process is not done properly, then there will be some expensive failures.

All pilots must understand that there are two kinds of limitations of a weapon system: hardware and human. The aircraft has definite limits of performance and maneuverability. Each pilot must know his own unique limitations and must know that his personal limitations vary from day to day. Commanders must fully appreciate the requirement for practice and proficiency when they ask their pilots to perform high workload tasks such as air to ground gunnery, air to air combat, or aerial demonstrations. Flying high-speed aircraft is a high-risk business; each pilot needs to be given the maximum chance of survival. Each pilot should understand how the mind works in order to maximize his own personal, unique capability.

The flight test community is limited in many ways so it is critical that we provide good pilot-vehicle analysis early in the design process. We are:

- Time limited--only so many hours in the day.
- People limited--a finite number of engineers and testers limits the ability to look at every possible new idea.

- Dollar limited--we cannot afford to flight test all of the different design options available to us.

Because of these real limitations we must:

- Study the pilot-aircraft system at an early point in the design process through realistic tests in order to give good total system performance.

- Prioritize the data displayed to the pilot because of the wide range of data available for display.

- Provide meaningful workload and performance data for decision makers early in the design process.

- Develop systems which accommodate individual pilot differences.

The penalties for not considering the human operator in aircraft design will always be with us. As technological sophistication grows, these penalties become increasingly unacceptable. If the complexity of aircraft and electronic warfare continues to increase, the human will have increasing difficulty in accomplishing his mission. The time is now if we are to reverse what has already become a disturbing aspect to defense acquisition and utilization of high performance aircraft.

Editor's Note: Concerning the concept of time-sharing, a work is in order regarding the mind's notion of time, or of the passage of time. Our notion of the passage of time is quite variable. Though the time to accomplish some over-learned task (or subconsciously core programmed task) is fairly consistent, the time to perform some relatively new task may be prolonged, and generally takes longer than one realizes. Among the variables affecting one's time sense are mental work, emotions, alertness and visual inputs, such as the pattern of flow in the peripheral visual fields. Thus, if one is concentrating intently on something, pressed, stressed, or otherwise fatigued, it's safer to assume that time flies, that things take longer than one thinks, especially if one is head-down so that the ambient visual mode is not updated or stimulated by the pattern of flow.

It is important therefore, to provide the pilot his critical aircraft control parameters (such as attitude, airspeed, altitude, and vertical velocity) as well as their trends, in a format that is instantly recognizable and that requires minimal expenditure of focal mode attentional resources. The ideal display is one that he doesn't even have to look at - that provides him the information he needs out of the corner of his eye or through other non-focal mode routes, such as hearing or proprioception. The present trend in the PVI is, however, to bypass the enormous information processing potential of these other routes and thrust it all upon the focal mode, thus tending to overload it.

Addendum: The following are points made by Col Milam in his remarks that were not in his paper.

- Longitudinal aircraft control:
  - Can see the pitch rate if you have a long nose
  - Can see the AOA, if you're looking at AOA gauge
  - Can feel the G's

- Human performance is a function of many factors including selection, training, and experience - and is subject to a fatiguing function. Human is adaptive and competitive in the simulator, if you think Joe Bill Dryden is going to beat me, you're crazy; and he feels the same. Successive decomposition: you prioritize and will overlook things.

- Workload: There's no good measure - must ask him - use Cooper/Bob Harper ratings. Fred Hoerner noted that when he gets busy, the first thing a pilot does is stop talking to you.

- Perilous attitudes - macho, anti-authority, impulsivity - I'm all of those.

- Memory - flash, short-term, long-term - no relation to IQ. Watching someone who's good and you can learn to mimic, to program your own cerebellum by repetition.

- Training: Throw your boy a ball first fime; hits him in the chest. "Boy, that's great". Keep building his confidence until pretty soon he does catch it. Success keeps building his confidence. He becomes the natural athlete. But can he coach? Never. Those who think about it become students of it.

- The super pilot doesn't think about what he does, or how he does it. He just does it. Keep your thinking and doing separate. The best way to screw him up is to get him thinking about it. Works great for gamesmanship at golf. Ask your opponent, "Boy, how do you do so well?" Nothing will screw him up more than getting him thinking about it.

- Self-confidence and concentration are really critical. Keep an eye on that ball - go in there with the attitude to win. Need state at that ball/rim (in basketball) for aiming reference. Conscious mind stares - sighting reference is critical. Zen vs. choaking up: If conscious mind is relaxed but alert, the body is also. There's a strong connection between the mind and the body.

- Learning: We learn by the rules, then forget the book. After 1,000 hours, who needs it? We learn not by logic but by comparison.

- Instruments: We stare at the ADI. A good instrument pilot has a highly methodical well-developed cross check, aided and abetted by the "Standard T". The same on the HUD plus a FPM, which like, others dislike.

- Foveal vision - your conscious mind - your desceptive. It's a series of conscious level tasks. By shooting the DART with a Lead Computing Optical Sight (LCOS). Relax, let the pipper drift up.

- Aerial Demo: Dangerous. Kills many good pilots. Operating close to the ground, there's no margin for error. Altitude is not critical: airspeed is. An unprogrammed event can be a killer - if you allow yourself to become distracted, you may never pick it up again. Altitude with the Paris A-10; pull with the Thunderbird T-38's. Need to program core: hit that tennis ball 100,000 times. Go sit in the Aircraft and mentally fly that airchow routine. Get mind and body relaxed. Let no unprogrammed event distract you. Only with practice can you learn - to learn to fly aircraft you must fly aircraft. Visualization and simulators both contribute to learning. Practice and proficiency is very important. Commander's responsibilities are that:

  1. Individual is well-trained.
  2. Individual is ready to fly.

- Proper visual cues

  HUD: is it optimized? Should it be individually/uniquely programmable?

  Pilots are unique: need 5 to 8 pilots to get good breadth of opinion. If over eight, force of personality tends to dominate the group. If less than five, have insufficient breadth.

  Engineer has a difficult task: what is great to one pilot may be rotten to another. How do you put those on a Bode Plot?

- Displays: need design aircraft so he can go heads up safely, or if he prefers, so he can go heads down safely. So his has that option: <u>especially with attitude.</u>

Editor's Note: Since the pilot spends so much time dwelling on the ADI, it would be ideal to provide him an attitude display he didn't need to stare at. The Peripheral Vision Horizon Display (AKA Malcolm Horizon) is designed to do just that: enable processing of attitude information by the ambient mode (natural orientation channel, while freeing up the focal mode for tasks requiring conscious attention.)

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DEVELOPING TRENDS IN AIRCRAFT CONTROL DISPLAYS

Mr. Peter Lovering
Midwest Systems Research, Inc.
Dayton, Ohio

BIOGRAPHY

- Joined the Air Force in 1952
- Completed Pilot Training in 1954, UPT Nellis AFB
- Completed F-86 Fighter Training in 1955
- Attended Phase I, AF All-Weather School in 1956 at Tyndall Air Force Base -- remained as an Instrument Instructor.
- OIC Instrument School, Elmendorf AFB, Alaska 1958-1961.
- Instructor, USAF IPIS, 1961-1966.
- In all, an Instructor/Flight Examiner for 17 years, retired from the regular Air Force in 1973.
- Employed by Bunker Ramo Corporation, Canoga Park, on a Pilot Factors Research contract with the Flight Dynamics Laboratory 1974-1981.
- From 1981 to present, involved in a small HUD symbology and mechanization study and in a sub-contract to Singer-Link Division on a number of KC-135 and F-16 C/D cockpit intergration and simulation tasks.
- TFT 8,000 hours - T-33, F-86 Dog, T-39, C-118.

Introduction

There has been increasing concern, in recent years, that there may be a situation awareness problem in modern and emerging fighter aircraft. Evidence of this concern is reflected in a 1980 review of possible pilot disorientation caused by the Head-Up Display (HUD) in F-15 aircraft, the convening of a HUD Instrument Conference at Langley AFB in June, 1983 and at least two recent instrument flight related F-16 incidents.

We in Midwest Systems Research, Inc., with over 80 years of combined experience in instrument instruction, operational flying, control and display design and instrument systems test and evaluation, share in that concern.

During the last three years our personnel have participated in a variety of LANTIRN and F-16 C/D simulator evaluations ranging from the original HUD symbology and mechanization studies for the LANTIRN A-10 and F-16 to the most recent F-16 Block 25B through 30G integration projects. During this time we have been in a position to "fly" the simulators in a wide variety of visual and instrument flight maneuvers, train pilots in system mechanization and operating procedures, and observe current crew members in the operation of "their aircraft." As a result of these experiences, we have identified a number of areas that we consider to be problems or potential problems in the safe and efficient operation of the aircraft. The F-16 is referred to throughout this paper because it has been the focal point of most of our work. This is not to imply that the issues apply only to the F-16; on the contrary, many of the same problems apply equally to other weapons systems such as the F-15, F/A-18, the C-17, and HH-60D.

A wide range of new technology is being introduced in the cockpits of new and emerging aircraft. Cockpits have become computerized; flight and navigation information is being presented in computer generated graphics; and classical electromechanical controls and displays are being replaced by electronic multi-functional devices.

Our primary area of concern focuses on the quality of these modern controls and displays as they pertain to keeping the pilot informed of his flight situation. In the following paragraphs we will try to discuss them in detail, pointing out the good and bad features, as we view them.

To establish a baseline, we have included a brief discussion of developments in instrument flight from about 1940 through current Flight Director applications. This has been done to stress the fact that today's conventional displays have evolved from years of careful manipulation of a controlled set of information that has been displayed and used in a pilot's control strategy. Each development (of any real significance) represents a substantive increase in precision and safety accompanied by a similar reduction in pilot workload. The attitude indicator, for example, made instrument flight easier. Similar improvements resulted from the integration of performance and navigation information in the HSI, as did the addition of Flight Director Steering commands on the ADI. These are examples of cases where more innformation was better. On the other hand, we believe we can show clearly that the integration and addition of HUD and other graphic display symbology can result in less precision and safety along with greatly increased pilot workload in several mission applications.

HUD in Instrument Flight

Early Developments

Instrument flying (Blind Flight) was made possible by the development and use of the gyro and, more specifically, the turn needle. It is well known that the human loses spatial orientation quickly in an aircraft without some outside references to keep several of his senses in line. In a cloud, a turn needle allowed the pilot to hold the aircraft in straight flight or in a controlled turn. This capability was enthusiastically welcomed by pilots because they discovered that they were finding the ground more often on purpose now than by mistake as had been the case in the past. Used properly, instrument flight time could be logged with much less excitement and longevity was increased by several orders of magnitude.

Needle Ball and Airspeed

There were two schools of thought on how the turn needle should be used. One advocated centering the needle with the rudders and the ball with the stick while the other stressed centering the ball with the rudders and the needle with the stick. Happily, both worked. The first procedure worked best in a spin recovery, the other in coordinating flight and the control process thereby preventing spins.

Procedures and techniques were developed to allow flight for short periods of time such as might be required for climb or descent through a cloud layer. Pilots could set power for a climb or descent, then, after assuring straight flight, use the stick to control pitch so that he held the proper climb or descent airspeed. It was about this time that people discovered some techniques that made "attitude" control easier without an attitude indicator. Altitude, airspeed, and vertical velocity movement reverses direction each time the nose of an aircraft passes through the horizon. Knowing this, the pilot could prevent large pitch excursions and control altitude and constant rate climbs and descents much more precisely. Instrument scan (or cross-check) was difficult at best and complicated by any turbulent flight conditions.

Later, these techniques were refined further, to the extent that, in relatively smooth air, an entire mission could be flown from takeoff to landing using these instrument procedures. The pilot could establish straight flight by centering the turn needle (bank control) then establishing level flight (or a constant rate climb or descent) by referring to the altimeter and vertical velocity indicator (pitch control). The airspeed indicator was used to determine power requirements. This "needle, ball and airspeed" method was used into the early 1950s even after early "artificial horizons" began appearing in the cockpit. During that time, Ocker, Crane, Duckworth, and others who understood and, in fact, developed many of these early procedures, were constantly working on displays and procedures that would make instrument flight safer and easier.

Primary Instrument System

In the 1950s, artificial horizons became more reliable and pilots began to use them more. Still, the performance displays remained as the basis for control. In this approach, three "primary" displays were used for pitch control, bank control, and power control for executing the instrument maneuvers which make up any mission.

In level flight, the altimeter was primary for pitch control, heading primary for bank control and airspeed primary for power control. In a constant airspeed climb or descent, airspeed was primary for pitch, heading for bank and the tachometer primary for power, etc. Actually, remembering what was primary for what in each maneuver was more difficult to learn (and teach) that flying the airplane. It did show, however, the reluctance to drastically change control and display concepts until a proven better method was available.

The attitude indicator became more popular during this time as reliability improved and displays such as the J-8, self-contained attitude indicator, were found to continue to operate reasonably well even after dynamic maneuvering. Precission rates in these displays were quite high, but with practice and a little understanding it would provide a stable reference from which corrections could be made quite easily. In the late 1950s and early 1960s, Attitude Instrument Flying procedures were developed and have been in use since then.

Attitude Instrument Flying

In 1940 the SAE (Society of Automotive Engineers) recommended a standard set of flight instruments. Their arrangement (basic six) was accepted for both military and civil use and specified in the HIAD (Handbook of Instructions for Aircraft Design). This arrangement, with some modification, remained as a specification until the middle 60s. One tried and tested configuration of the basic six is shown below (Fig 1).

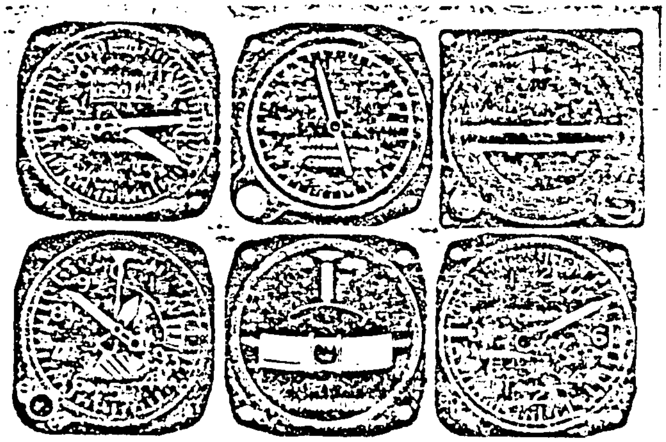


Figure 1: Basic Six Instrument Arrangement

In the early 40s, Sigfried Knemeyer, then in Germany, had the foresight and unique understanding of control and display concepts to recommend installation of the attitude indicator at the center of the instrument group. Later (1947-1948) at Wright Field, he was at the forefront of Flight Director development, and again recommended moving beyond the "basic six" arrangement. There were two basic Flight Director configurations, one using standard round dials and another using vertical scale instruments. These arrangements are shown in Figure 2.

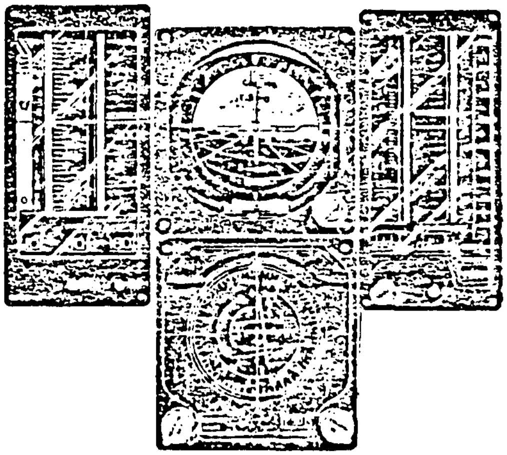


Figure 2: Flight Director Configurations

Introduction of Flight Director steering was, in early systems, limited to ILS pitch and bank steering for final approach and landing. A manual heading command was also available. Later, features such as rotation and go-around, altitude hold and VOR/TACAN steering were added.

Primary strengths in the Flight Director arrangement (in addition to command steering) were: 1) ADI size was increased to 5" and it was placed at the center of the instrument scan; 2) heading, bearing, and course deviation information was integrated into a single, and larger, HSI; and 3) the number of instruments required for aircraft control and navigation was reduced from 7 to 8 to 5. A big plus for the vertical scale configuration was the fact that there was only one logical way to put the system in the cockpit-standardization by design.

By this time more production aircraft had newer more reliable attitude displays that would operate well in a wide range of nmaneuvers. The 3-axis gyro platform, for example, allowed full freedom of maneuvering without "tumbling", "controlled precession" or the introduction of large errors.

Attitude instrument flying is very similar to the way a pilot flies, and thinks, in visual flight conditions. Cockpit displays are divided into four groups; control, performance, navigation and steering.

Control Instruments. The attitude indicator and power displays provide information for control inputs.

Performance Instruments. Airspeed, altitude, heading, vertical velocity, and angle-of-attack show aircraft performance.

Navigation Instruments. Bearing, distance, and course deviation displays provide position and situation information.

Steering Instruments. Flight Director computations provide commanded attitude and performance of a limited set of maneuvers such as rotation and go-around, ILS approaches and VOR/TACAN navigation.

Today, a pilot established an aircraft attitude and power setting that he knows, from visual flight, will approximate what he wants to do. He does this by reference ot the control instruments. Next, he scans performance displays to see if performance is what it should be. If discrepancies exist, he makes appropriate changes on the control set and, again, checks performance to verify that changes in attitude or power had the proper effect. This is a continuous process in maneuvering flight, made relatively simple by trimming the aircraft properly and maintaining a reasonable degree of proficiency.

Once the pilot has the aircraft under control and desired performance has been achieved, he refers to navigation displays to determine where he is and where he wants to be. When corrections are indicated by the navigation displays it's back to the control and performance instruments to make the changes.

The final category, command steering, combines signals from the control group (attitude), the performance group (heading) and the navigation group (course error, course deviation, glideslope deviation, etc.) and performs essentially the same integration of information as the pilot. Specific information needs vary with the various operating modes. Steering commands make the control task much easier by limiting pitch and bank changes to a set of limits consistent with the amount of deviation (stabilize the aircraft) and by performing one or more levels of calculation previously required of the pilot. He can follow the commands and watch the system work, effectively cross-checking steering quality, while monitoring attitude and heading, etc. to see that all parts of the system are responding properly.

By the middle 1960s, virtually all military aircraft in production were equipped either with a resonably standard set of "round dial" instruments, a Flight Director System or the Integrated Flight Instrument System (Flight

Director and Vertical Scale Instruments). With these systems, a standard approach could be taken in training and in operational applications. Pilots could transition from one display configuration to another with relative ease because display parameters were used the same way in all three configurations.

There were, apparently at least, some very significant changes in the perceived importance of proficiency and instrument training in the 1970s. The fuel crunch and increasing flying hour costs led to a reduction in instrument flight hours in pilot training. Proficiency flying for "behind-the-line" pilots was virtually eliminated, and in 1978, the Instrument Flight Center (previously the Instrument Pilot Instructor School) was closed as an economy measure ending 35 years of support to the Air Force. Until this time, the IFC served as the Air Force focal point for instrument training, flight procedures development, and instrument systems evaluation and testing. The combined effects of these actions reduced total flying hours and focused attention on weapons delivery aspects of the Air Force Mission. Ripple effects reached the R&D community where programs that did not address bombs or bullets on target were put in file thirteen. These actions were not only unfortunate but also very untimely because they were taken just as the gun/bombsight became a head up display, cockpits were computerized and the glass cockpit emerged. To add further complexity, the Air Force make a frontal attack on the night, in and under the weather, air-to-ground mission with LANTIRN; a mission that requires a new form of instrument flight in a very different environment. As a result, we feel that there exists a five to seven year void in serious consideration of the instrument flight aspects of a near revolution in cockpit control and display design. Actually, many of these changes have evolved because technology allowed (sometimes required) it to happen. In our opinion, changes of this magnitude should be driven by the mission and pilot information and control needs to accomplish the mission.

Recent Developments

The following paragraphs will address specific issues in existing and emerging cockpits and operating procedures.

Situation Awareness

The term situation awareness is relatively new and used primarily in the fighter would to describe the wide range of conditions that lead to successful and safe mission accomplishment. Loss of an aircraft because the pilot becomes spatially disoriented is often attributed to his loss of situation awareness.

It seems that a very generic term has evolved to describe several pieces of an overall mission scenario. Pieces of the situation awareness picture include location of a wingman, target or IP location; cloud ceiling, visibility, the threat, aircraft attitude, engine condition, speed, TOT, altitude and a wide range of others. Of primary importance, however, is the attitutde and performance of the pilot's own airplane. Unless he is confident of exactly what his aircraft is doing, the other pieces of the awareness picture are meaningless. Actually, all of the relavent parts of the situation awarenss picture can be placed on a list; one that changes almost constantly. The pilot's job is to prioritize items on the list in the dynamics of the environment in which he operates. While many items (oil pressure, target identification, INS update) range from near the top to the bottom of the list during any given mission, flying the airplane is always on top. This fact, we believe, needs to be clearly understood not only by pilots, but by display systems and aircraft designers as well. Given the opportunity to do so, we would remove aircraft control and performance from the situation awareness description and place it on a level of importance with all that remains.

New Missions and Displays

Advancements in weapons, sensors, integration techniques and computer power make it possible to perform old missions with greater precision and efficiency and, at the same time, open the door to the potential for new applications. The AMRAAM, for example, will lead to some interesting changes in Air-to-Air operations while LANTIRN integrations is of special interest because night, single seat in and under the weather interdiction and low level operation in this environment is new. Because it is new, a close look at potential and implied instrument flight related problems might reveal a few than can be addressed before they are encountered operationally. Some of these are discussed below along with candidate solutions.

Attitude Displays

As electromechanical attitude displays evolved, the range of attitude shown at any given time increased from 20-30 degrees of pitch attitude and 40-80 degree of roll to the 5" ADI that is, in fact, all attitude and displays approximately 100 degrees of pitch, 360 degrees of roll and, in the F-4 3 axis ADI, over 100 degree of heading information. This expansion occurred in a period when designers were trying to expand the envelope in which a pilot could operate an aircraft in limited visibility conditions. One early attitude indicator, shown in Figure 3, probably operated in the + - 10 - to 20 degrees of pitch range.

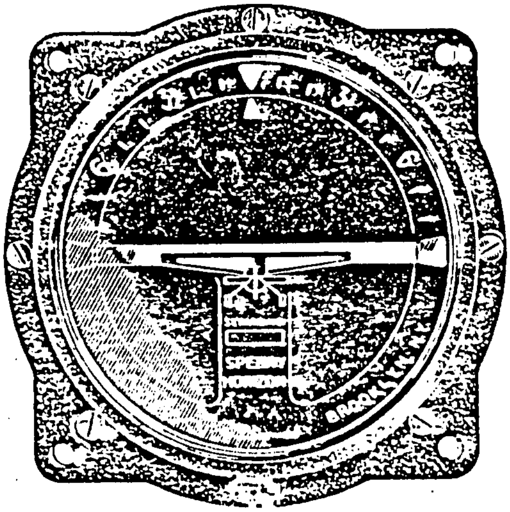


Figure 3: Early Attitude Indicator

Demands of the transition to jet powered aircraft with much wider operating envelopes and continuing improvement in gyroscopic instrument design led to newer displays like the J-8 shown in figure 4. With this instrument, pilots could roll through 360 degrees without fear of the instrument "tumbling." A mechanical horizon bar, somewhat unorthodox by today's standards, moved vertically through 27 degrees of pitch (+ - 13.5 degrees from level flight.

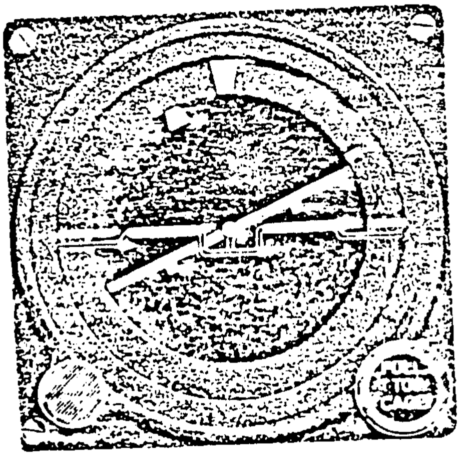


Figure 4: J-8 Attitude Indicator

The dead-down instrument systems in emerging cockpits are designed such that the pilot is driven to the HUD for at least part of his cross-check. The problem with this is that the HUD is designed around inertial path angle, not attitude, and during periods of poor visibility he must rely on a performance display for pitch attitude control. Primary areas of concern are that, unlike the ADI, the point of reference (FPM) in the HUD mover vertically over slightly more than half of the HUD surface as a function of angle of attack (AOA), the ability of the pilot to determine pitch and bank attitude accurately is limited and deteriorates with increasing AOA, and the utility of the display is very energy dependent, i.e., at high AOA the FPM can reach the HUD FOV limit and become essentially useless.

Another feature that is lacking in the F-16 and, most of the time, in the FA-18 HUD is a miniature aircraft symbol. In order for the HUD to show attitude, the symbol should be placed in a position on the HUD to represent an extention of the Fuselage Reference Line (FRL). While the ability of current HUDs is limited in this regard, the addition of this symbol, at least in several appropriate operating modes, would enhance the pilots ability to control aircraft pitch attitude. Some applicable maneuvers include:

1. Takeoff at night or in limited visibility.
2. Initial climb (as path angle is stabilizing).
3. Missed Approach.
4. Other maneuvers as the pilot sees fit at speeds close to or above normal cruise.

Pitch changes using this display were made in bar widths with one bar width equal to approximately one degree. When the horizon bar reached the upper or lower limit the aircraft would, in a loop for example, continue to fly around a kidney shaped portion of a sphere until a circle (white up, black down) with the words climb or dive appeared. At 85 degrees-90 degrees of pitch, the display would rotate 180 degrees allowing the pilot to continue another 180 degrees of pitch change before it again rotated to allow a return to level flight.

Procedures for unusual attitude recoveries using the J-8 were somewhat mechanical but effective. The bank pointer allows pointed up (sky pointer) and when they were in separate halves, the nose was high.

The MM-Series of attitude indicators eliminated the horizon bar, displayed a contrasting sky/ground relationship through the use of color coding and covered a wider range of pitch by showing 50 to 60 degrees on the MM-2 and 3 and 110 degrees on the MM-1 and 4. These displays, shown in Figure 5, were carried into the flight director and Integrated Flight Instrument System designs and have remained as a relatively standard display format in aircraft through the F-15 and F-16.

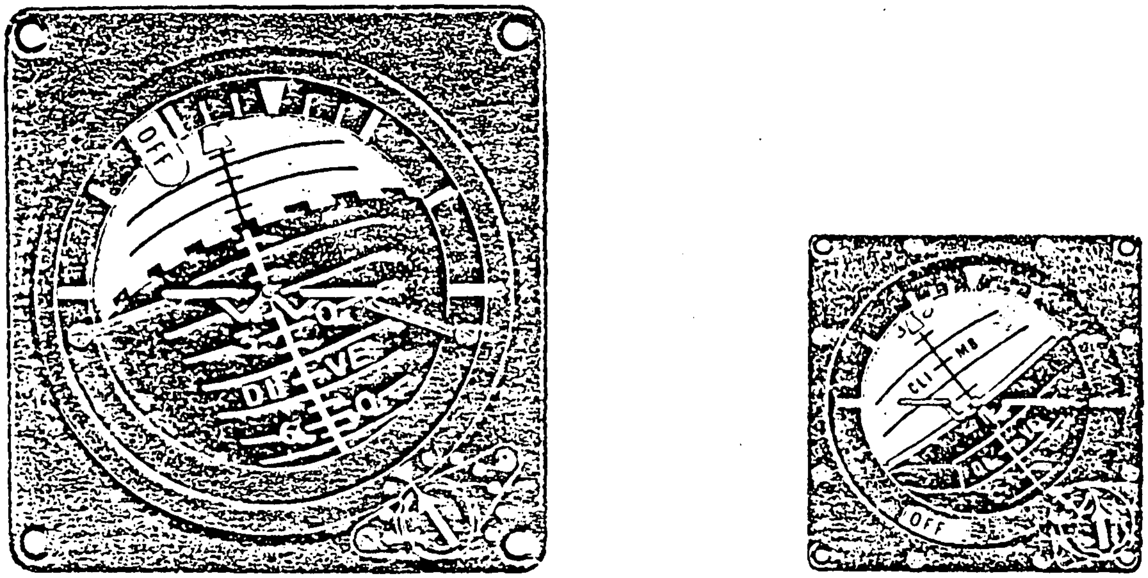


Figure 5: MM-Series Displays

Heading Displays

A problem very similar to that discussed in regard to attitude also exists with heading displays. These displays on the HUD and many head down VSDs show roughly 10 percent of the 360 degree compass rose as did the Directional Gyro (DG) in a 1940s vintage T-6 trainer. Radio Magnetic Indicators (RMI), Compass Cards and Horizontal Situation Indicator (HSI) were designed specifically to provide the pilot with a 360 degree view of the navigation (orientation) situation. These devices are used frequently to determine reciprocal headings and bearings in addition to providing, at a glance, direction and degrees of turn to a predetermined heading or intercept angle. Lacking this kind of picture of the navigation situation and into addition and subtraction tasks. Being of superior intellect, pilots do not find this difficult, merely time consuming, often when other more critical issues must be considered.

Similar arguments can be made with regard to altitude, navigation and some airspeed displays on the new graphic displays. Actually the only display feature on the LANTIRN HUD with a wide field of regard is the Steerpoint Index (in reality it is a bearing pointer) with the capability of indicating 360 degrees if relative bearing to the selected steerpoint.

Conclusions

It can be seen that the evolution of instrument flight into the 1970s has been paced more by the way pilots and designers learned to use information than by changes in the information being used. There is over forty years of experience (good and bad) behind the way pilots are trained to fly in poor visibility and procedures and techniques in use were adopted only after very careful consideration, testing, and validation. Any attempt to change information parameters, major alteration in display format or dynamics or changes in the way the information is used by pilots should be considered only after the changes are proven to be superior to those already in use.

Recent introduction of graphic display technology has been much more than a media change, it is changing the way we must train pilots and fly airplanes - and it is leading to a change in cockpit workload associated with attitude and flight path control. In any assessment of the utility of those new display, and the environment in which it was created.

The HUD was designed to be the micrometer in an air-to-air and air-to-ground weapon delivery task. It was conceived in a visual environment where the pilot used his wide field of regard (in excess of 180 degrees vertically and laterally) to steer the aircraft to the intended target. To do this he had the full range of foveal and peripheral cues with which to remain oriented with respect to the earth, the horizon, and the target. Once the target was in front of the aircraft and in the HUD FOV, delivery symbology could be used effectively to complete the job, and it does this very well.

If the full visual scene is removed by darkness, for example, as it is in the LANTIRN environment, then the pilot's field of view of the outside world is reduced to 20 x 30 degrees with a corresponding loss of the peripheral cues for orientation and target alignment. He must then use lateral steering cues to find the target and only 20 degrees of vertical situation information for orientation in the vertical axis. If high humidity degrades the FLIR scene, then all outside visual cues are lost and orientation must be maintained with the steerpoint cue, TF cue and radar altitmeter, and limited indications of attitude. In this final configuration, the pilot cannot revert to head down displays without losing the only information (TF Cue) that keeps him from hitting the ground. His only recourse at this point to to depart the low level environment and attempt to find visual flight conditions. Accordingly, the evaluator needs to look at worst case conditions to determine total system capabilties in the new environment the system is likely to encounter.

AIR FORCE INSTRUMENT FLIGHT TRAINING
AND ITS HISTORY

LTC William R. Ercoline
USAF IFC/OP
Randolph AFB, Texas

BIOGRAPHY

Our next speaker is Lt. Col Bill Ercoline. Bill is the chief of Operational Plans and Programs Division of the Air Force Instrument Flight Center at Randolph Air Force Base. His background includes a Bachelor of Arts, Bachelor of Science in Physics with California State College and an MS in Laser Optics from AFIT. He is a graduate of the Air War College, he instructed physics at the Air Force Academy, flew combat in the C-130, total flying time is 3200 hours, he's instructed over 2000 hours including the instrument pilot inspector school, before that closed. Investigated instrument related mishaps involving the F-16 and RC 135. He's flown the Crane all-weather flight gauge, and he's currently making a formal evaluation on the use of that device. And he'll speak to us this morning on Air Force Instrument Flight Training. Bill.

I have a lot of information to try and pass on to you in the form of this presentation so I was trying to use some of the information that I have picked up over the last day and a little bit of time here. So I thought maybe I would project 30 slides and let your subconscious pick it all up and then I would just tell you that your subconscious has it all and then we don't have to go through each slide in sequence. But Col McNaughton couldn't provide me with 30 projectors so we are going to have to go through the slides. The way I have this information organized is, I, too, am going to give you a little background of history. A little bit about the things we are talking about today: where it all came from. Then I'll talk about the instrument training method that we used in the Air Training Command to teach all Air Force pilots how to fly instruments. Then we will talk a little about the practices throughout the Air Force. I also want to throw in a little bit about attitude display which is very apropose for today and hopefully show you a different way, which maybe a lot of you are familiar with. And then with some time remaining, a couple of minutes, I would like my boss, Col Baker, who is in the audience here, to critique me, to maybe say something about the instrument flight center, what we are tasked to do and what, in fact, we are trying to do there.

So to start with, I'd like to go through some slides here. Before I do that though, I'd like to take you back in time for a minute and show you the first instrument that ever came about. The Wright Brothers came up with this (holding up a piece of string). This is a string that they tied to the strut of their aircraft to blow right back in their face. They could tell if they were descending or climbing, slipping or sliding. It provided them with a lot of information. And they taught pilots to use it. As a matter of fact, this piece of string was common on all the early Wright Flyers. They got information from and after we became quite proficient in flying we did all our flying VFR. They abandoned it, they went away from it. As a matter of fact, the instructors early on decided to tell their students they wanted them to develop a "feel of the ship." From that sprung up the myth of having that innate ability to fly the airplane.

With the advent of having to fly in fog and WWII, because of that myth, we ended up losing a lot of people. A lot of pilots, and we evolved into a different system and eventually we came up with something like this A-7 cockpit. We got there through a large number of years and through a lot of accidents and a large number of experiments.

We eventually got up to something like this and now we have gone beyond that which I'll talk about later, but this is what we call the T-cross check, which you've heard before: you have your attitude Indicator in the center, down below your HSI, airspeed, altimeter; and it gives you the basic T. It's in most of our airplanes today, and I say that talking about Air Force. This is a C-5 cockpit. You can see the same layout. By the way, this cockpit arrangement is an FAA requirement for commercial flight operations. There is a regulation that defines the T, what instruments are placed where, and even if you stick something in between, that then becomes a primary instrument. So there is something to this, to this arrangement. It gives us bits of information that we try to construct, as someone mentioned yesterday, to give us somehing like the real world. It doesn't give us the real world, but it provides us with something in here that we build on to and that somehow translates to the real world.

Well, how did we get there? I'm going to tell you some information that I received from this man, Col Carl Paul Crane, who I had the good fortune to fly with in the mid '70s, and late '70s and even early '80s. Carl passed away about 3 years ago in 1982, and he had quite a story to tell, and perhaps some of you have heard that story before. I want to give you some of the historical information because I think it is important. His ideas were innovative throughout his life and I think he left a lot with us that we are talking about today and the story that he told definately started the information that we are talking about today. And I want to leave you with a little bit of that before I get into instrument training.

In 1923, Lt John Macready flew his first flight from the West to the East coast, he tried several times east to west but he never made it so he finally made it west to east. It was a significant event at that time but the significant thing, I thought, was the report that he wrote in which he said in one of his quotes: (reported in <u>National Geographic</u> in 1924) he said at that time that he felt he could not maintain his aircraft if there was not some visual reference, a point, a light, a horizon, some cloud out on the horizon that would help him maintain his aircraft. Now, he published that in 1924. At that time the attitude was that we did not need instruments to maintain aircraft control. Now, who was Macready? Well, he happended to be one of the chief test pilots at McCook Field. He set an altitude record, he did a lot of other things too.

But the thinking at that time was, there was something happening to our pilots when they would go into weather. We needed more information, but we really weren't sure because they had been trained in a VFR environment where they had that big picture and it was not the thing to admit that you couldn't fly when you went into weather. So we had a problem here. We had a lot of pilots; we had instruments on the airplane then; we had turn and bank indicators. A lot of times the pilots would send them back to the manufacturers saying that they didn't work when they went into weather. They worked fine when they were VFR. And they would be benched and they would be sent back saying, "checked good, OPS checked okay."

All right, well, how do we get to those cockpits I showed you earlier: the T-cross check. In order to talk about that, to give you a better feel of what was going on then, this was the top-line fighter in 1925. I want to show you the cockpit of that airplane. You had some instruments there that dealt with the engine, but you would be hard pressed to find the bank and turn indicator, the turn bank indicator and the mag compass were hard to see because they were mounted on the floor between the rudder petals. It's not on this slide but one of these lines would show you where it is. The bank indicator was mounted on the floor and the compass was mounted on top of it. As a matter of fact, some commanders in their outfit had those things taped over because they wanted the pilots to develop this innate ability to fly.

As a matter of fact, at that time even prior to going into pilot training, we had what was called a Ruggles Orientator in which you would be examined. It was a chair that could be moved around on two axes of motion, and you would be examined based on how well you could perform after being spun around in this chair. And that could determine whether you would make it through pilot training, whether you would even enter and get a chance at it. That was the attitude.

Now how did we get through all that? This is a picture of the entire air force in 1913. I'll have to take you back in time. These are the officers in the front row. This is Lt Foulois. But it's the back row I want to talk just a minute about because there is a person back there, right here, a tall man; he is the only one that has two medals on, and he was an enlisted person at the time and his name is Bill Ocker, and he is the one who really discovered the problem that we have been talking about for the last day. His story is quite interesting and I'm going to briefly talk about that.

This is Col Ocker about 3 months before he passed away in 1942. He discovered what this problem was that pilots were experiencing at the time and he paid dearly for it. He was twice sent to Letterman General Hospital for psychiatric evaluation because he had to tell pilots about what was going on. His commanding officer decided he was nuts. He later in life, he claimed to be, he kind of joked about it, he claimed to be the only officer, in the Air Corps at the time that had two letters that proved he was sane. He suffered the humiliation of a Court Martial, because of an arguement he had with the commanding officer. He was aquitted on that, but he paid dearly for it. He was never really recognized for his contributions and I want to leave you with a little bit of what he did, and how that happened.

Col Ocker was given one of the first turn/bank indicators that Elmer Sperry made in 1918. And he carried that thing religiously with him on every flight for eight years before he realized what it was all about. He, too, did not believe it. He felt it worked fine in clear weather conditions, but when he went into clouds or something like that it just didn't work right. And could you imagine going out on a sortie with this guy, "Wait just a minute, I have to get my turn and bank indicator!" He'd mount that thing on the strut of the airplane and away they'd go. Now, he took that thing with him for eight years. In 1926, a Capt Meyer, flight surgeon, was giving him his semi-annual physical. Capt Meyers would put pilots in the Jones-Barany chair. He would blindfold them and spin them and have them guess which way they were spinning. No one could ever get it correctly. Now, no one had as yet ever associated that with the problems we were having at the time about flying in weather. He put Ocker in this chair in 1926, blindfolded him and spun him up. And sure enough Ocker couldn't get the directions correct.

So what happened next was kind of interesting. Because that really changed our attitude or our understanding of instrument flying and what we needed to fly. Ocker recalled an earlier incident when he was flying with Billy Mitchell. He was Billy Mitchell's aid for a couple of years. He was in the back seat of an airplane and they were checking out a new field location and he noticed some oil on his shoe. As Billy Mitchell was banking the airplane to the right, he bent over to wipe the oil off his shoe and he felt that the airplane leveled off and started to turn to the left. And he was kind of surprised when he straightened up and found that they were flying straight and level. Now, that was earlier in the '20s that that had happened. He never really correlated that with anything until this incident with Capt Meyer. And what he did, he asked Dr Meyers if he could come back and have this test again. And Dr Meyers said, "Sure; anything to fool you dumb pilots." So Ocker went back to his room, he got this turn indicator that Sperry had given him, he mounted it in a light type box, he put a flashlight in there and he put a magnetic compass in. And he had a little hose that he could blow in to get the gyro spinning. He went back into Meyers' office and this time instead of being blindfolded he put that box over his face. And

Meyers spun him in that chair and sure enough, he got the right direction every time. That was the first internationally accepted discovery of pilot vertigo and that has never been challenged. That's what started it all.

Now Ocher did quite a bit after that, but as I mentioned earlier, he paid the price for that because at that time we wanted people to have that natural ability to fly. Little did we realize that it was something else. Now, Ocker put the box there, and he used to try and convince people that you needed this type of training. Later in the '20s, he met Carl Crane, who was then a lieutenant. Carl had a similar incident that Ocker had had, that kindled his interest about instrument flying. He learned something more because of a spin he had gotten himself into. And Ocker gave him some answers and that really made Carl Crane a believer, and that's what perpetuated Crane's story, but this was in the late '20s.

In 1970, the FAA finally decided it was a good idea and they had their flight check people go out with a little gyro box to show people how you become disoriented. So it takes a little time to get new ideas across.

But why do I have a pigeon here covered up? I wanted to tell you just a couple of things these guys had to go through to convince people. People wanted them to fly like birds. Well, Crane came up with the idea that birds really don't fly that way either. They had to show people. So what did they do? They took some birds, some pigeons here, and they would cover their heads up, take them up in the airplane and throw them out of the airplane. And sure enough, the birds would become disorientated, but they were smart, they would put their wings out at a wide dihedral and just float down to earth. You take their bag off and they'd fly away. So little by little, these were some of the things they had to go through to convince people that you can't do it like a bird. They also blindfolded people and gave them a line marker and kind of let them go in a straight line and you would see that everybody started a spiral tendancy. So little by little we began to believe there was something there.

We started to look into instrument conditions and what we need. Crane and Ocker both devised, by putting some instruments on this old Ruggles Orientator, the first simulator. Later with the idea of two scientists, Diamond and Dunsmore, who were working on the model airways, Carl Crane put together a simulator which actually had course guidance in it, and he patented that.

Now, about a year after that patent was filed, the patent office notified him that there was a conflict here. Someone by the name of Ed Link had filed a similar patent and they had to resolve the issue. Well, over the process of a lengthy investigation they determined Crane was two years ahead of Ed Link. Link was forced to take a patent out under Crane. Now, I say that because we all have heard of Link. Very few have probably heard of Crane, and I say that because this was the first simulator that had instrument course guidance in it. That started with Crane's idea, which he got from Ocker and some of the needs they had in those days. When you think about how much we do today in instrument flying in the simulator, you can appreciate the magnitude of this idea that happened way back then.

About the same time, under the auspices of the Guggenheim Fund, Jimmy Doolittle made the first blind flight from takeoff to landing in 1929. This was the first artificial horizon in the airplane. There was also a new altimeter called the Kollsman altimeter and the first directional indicator was in that airplane. From this, I feel, the seed was planted for the instrument panel that we have today. If you look at this panel and what was done then, which is very significant, you look at the Sperry system that came out in the '50s, you can find the attitude display still somewhere in the middle. Between that period, believe me, it was moved around a lot.

So we are going through quite a large period of time here and then after this system it was improvised a little bit to get you back where we are today, but notice not much really changed. We changed the sky color a little bit. The ground has always remained black or brown, dark, but the arrangement is there and we developed the T cross check from that. That's how we got to where we are today.

What I want to do next, after having gone through about 70 years of instrument conditions, I would like to tell you a little bit about how we do it in the Air Force, how we train people that are completely unfamiliar with instrument flying, how we train them to fly their airplanes. Now that is the guy we are giving undergraduate pilot training. That may change a little bit once he gets in his aircraft, but this is the information that he is given at pilot training.

Now I'm going to have to change my media presentation here. So could you turn that off please? I'm sure most of us in the room are familiar with this cockpit. It's the T-38. Again, the arrangement, the T cross check, this was the standard for a long time. And we go back to the '60s all the way up to the present day. And we still plan on using this. The plan is to use this all the way up to the year 2000. I know of no plan that has been funded to modify the instrument arrangement. That may change if some things develop here, but even the T-46, if it ever gets the bugs worked out of it, will have this type of arrangement in it. This is what the pilot, this is how the pilot is going to learn to fly instruments. This is the cockpit.

Now, how do we teach him, what do we teach him? I think Pete Lovering discussed a little of this, but I wanted to take something out of 51-37. This is a copy of a little chart that is in 51-37. It is exact. What we do for a guy to learn to fly instruments from that instrument panel, is that we break the instruments down. We try to piece them together so I guess in his conscious mind, if I understood some of the talks yesterday, we want to give him a series of events that he can comprehend, to put together, to construct that real world. So what we do, we take those instruments and break them into three categories: control, performance and navigation. Some people may say that there is another category that you can call command information. We could discuss that, but I think just for the sake of not having an arguement right now, let's just leave it at these three categories. You can see under certain conditions, your horizontal situation indicators could fall under either performance or navigation, depending on how you use them.

What is taught to those people is that we maintain attitude of the airplane with the control instruments. That's how they get the name "control". They are calibrated in order to allow the pilot to make exact input into his aircraft. Attitude and power, be it the tachometer, the EGT, the FTIT, depending on what airplane you are flying, you could get that power from a various number of instruments. But that is how he is taught to control his airplane. He maintains aircraft control by establishing a cross-check based on control instruments. From that he works on what we call the cross-check, where he goes from his control instruments to his performance instruments.

The performance instruments are those instruments that give him information to see how his aircraft is performing. Sometimes they lag; it depends; and depending on his instructor and his knowledge, he will try to convey to the student how these interrelate. That's how he learns to fly instruments. And you can go through the performance instruments.

Notice the HUD is not here because 51-37 has not been updated to include the HUD. We feel at the Instrument Flight Center, that the HUD will fall under a performance instrument. Presently, present HUDs will. Until some changes are made, we are hesitant to put it in the control instrument column.

But this is the way he learns. We have to have a sequence to teach this guy. We can't just let him go out in an airplane and learn on his own and then, "How did you do it?" "Well I don't know." We have to evaluate him, we have to critique him on what he does. In order to do that there has to be some kind of event, some series of events that we can critique. And we have to give him information. There are just too many people to be able to handle it on a one-to-one basis. There has to be some standardization to this whole process. And that's a problem we face. But any way, that's the way we do it. And with that we develop a cross-check and we use the cockpit of the T-38 to work that cross-check and that's how he learns to fly instruments. And that's how he will learn to fly instruments for a long time, too. That's not changing.

However, other things are changing. As you can see here, I just want to show you some other cockpits. We have seen quite a few, so I won't bore you with too many. But I want to show you some of the things the pilot is going to be exposed to and some of the things we are going to have to put back into that training. Or, we are going to have to come up with a sequence of events that allow us to do it consistently over and over again so that we develop some type of distribution whereby we can say this guy is the cut off point, and everybody below that point doesn't fit. It has to be done.

As you can see here, these are standby instruments but the B-1, this will be an attitude display, can be, your HSI is below it, you have some tape instruments, but the standby group of instruments here. So, something goes wrong here, he is going to have to develop a cross-check on the standby down to the HSI to get his directional information. So, a little large cross-check there, but that would be in an emergency situation.

F-16 C/D cockpit. Again, we buried the instruments a little lower in the cockpit, but I think the integrety here is pretty close. But again, you have the option. You have the ADI here, you have attitude display, although it is not an attitude indicator, up here so you can get something out of that.

I'll give you a couple of the quickies here. Here is the F-15 E cockpit. There is no attitude indicator per se, as we know it in the T-38. However, you can call up something that looks just like it. Anywhere you want. So I'm a little puzzled with that, I'm a little concerned about it too, because if you. . the C-17 cockpit is changed, that's a proposal, and they have some information here about, again the pilot has the option and that's one of the things that concerns me. It concerns me that we have given the pilot a lot of options here. Maybe that's good, maybe that's bad; but I'll tell you what, they do not have that option while they are learning to fly instruments. They are told the way to do it and they try to perform to that level. And then we put them in an environment where they have a lot of options. Now whether that's good or bad I'm not sure. But that's the way it is.

I did want to talk a little bit about attitude displays because what I tried to show you there was some of the problems we had. I want to go back and come up and show you what Carl Crane came up with years ago, back in the '30s really. And we kind of took a different road in our attitude displays. Whether that was good or bad, I'm not sure but I do have some mixed emotions, mixed feelings on this issue and I'm sure some of you do, too. What Carl felt was, over on the left there is our current attitude display (ADI). This is what is actually happening in the airplane. If I understood some people correctly yesterday, that information on the left of that slide is not the way we see it as it actually happens when we are flying an airplane, in the roll sense. I'm talking about the roll sense; pitch seems to be correct. But there is a conflict here. We build a picture based on that representation over there and I'll tell you, it takes a while for a student to learn to interpret that roll information. And as Col McNaughton said yesterday, for some people, it never really does become automatic, although you can learn to use it. To master this, you can do it. It takes time to learn it. How much time? I think we have a handle on that.

This, the Crane Alweather Flitegage, though doesn't seem to take that much time, and I bet there isn't anyone in here, (and there's not even an attitude horizon line on this) but I bet you everyone in this room knows which way to push the stick to level those wings. All right? This is what you see when you are flying an airplane. I think is that, yeah? I don't know if the next slide is really going to show what I want it to. Yeah, it's in a bank now. The horizon doesn't turn, its stationary. It's always been that way, and that's what we see when we ride a bike, do whatever we do, that's what we see. That's what our mind picks up and that's what we are conditioned to. Somehow our instruments do not quite do that. This is what our instrument displays, if you will: the horizon turns. Carl Crane felt there was something more that you should see. You should see the airplane actually turn, the horizon stationary. And he devised, he and Ocker both, by the way, they also published the first training manual that was ever written. They wrote a book called Blind Flying in Theory and Practice, published in 1932 in San Antonio. And it was the first book that talked about how to teach people to fly in instrument conditions. What they felt, this was called your outside-in display. All right, where you're outside from the God's-eye view looking in and you fly your airplane that way. There's been a lot of research done on this. But I'll just mention that. I want to show you, to get a feel for what's going on here. That's a climb, and I don't want to get into all this other stuff. I just want to you to be aware of the attitude display. I think that's what's important. This is a right bank. If you want to roll left, you just roll the airplane left. Okay, that's called an outside-in display. Very simple. It seems to work well. They'll probably do more tests on it, but you get into an interesting discussion when you do this because we've gone down that other road for a lot of years. There's a lot of equipment out there that says we do it the other way. And that's something that I don't know if we will ever overcome.

But I want to leave you with this information because this is another way of doing it. And it seems like there is more of the big picture here. You don't have to piece little parts of information and construct that picture in your mind. It's here, it's the way we do things from day number 1; we see it out there and we learn it that way. We get out in the airplane, and it's very intuitive and natural. It's our subconscious working. I think the Inside-out way requires more conscious processing and never does become as inherently obvious and automatic as the outside-in (God's eye view) presentation.

NEEDS OF INSTRUMENT FLIGHT CENTER

Colonel Jay Baker
Commander, USAF Instrument Flight Center
Randolph AFB, Texas

BIOGRAPHY

Colonel E.J. Baker is commander of the U.S. Air Force Instrument Flight Center located at Randolph Air Base, Texas. The center is the central focal point for all instrument flight related functions in the Air Force.

Colonel Baker was born on February 16, 1938 near Batesville, Arkansas. He graduated from Hoisington High School, Hoisington, Kansas, in 1956 and then attended Wichita State University, Wichita Kansas, where he received a bachelor of education degree in June 1962. Upon graduation, he was commissioned as a second lieutenant through the Air Force Reserve Officers' Training Corps program. He completed Air Command and Staff College in 1975 and Industrial College of the Armed Forces in 1977.

In July 1962, the colonel entered active duty and began pilot training. Colonel Baker received his pilot wings in August 1963 at Vance Air Force Base, Oklahoma. He then completed pilot instructor training at Williams Air Force Base, Arizona.

From November 1963 to September 1966, he was an instructor pilot with the 3560th Flying Training Wing at Webb Air Force Base, Texas. He instructed in both the T-37 and T-38 aircraft and was selected as a wing T-38 standardization and evaluation flight examiner in 1965.

In October 1966, Colonel Baker began F-4 combat air crew training at MacDill Air Force Base, Florida. He was next assigned to Seymour Johnson Air Force Base, North Carolina, as part of the initial fighter pilot cadre to convert the 4th Tactical Fighter Wing from F-105 to F-4 aircraft. From January to July 1968 he was deployed with the Wing to Kunsan Air Base, South Korea during the Pueblo crisis. In November 1968, he was selected as deputy chief of Wing Operations Plans where he was responsible for planning the first ever deployment of Tactical Air Commands Bare Base equipment and personnel to North Field, South Carolina.

Colonel Baker transferred to Udorn Royal Thai Air Force Base, Thailand in July 1970 and was assigned to Detachment 1, 56th Special Operations Wing. During his Southeast Asia tour of duty, he was a fighter pilot and weapons and tactics officer while flying combat missions in the AT-28 over Laos and Cambodia.

The colonel next had a four year assignment to Vance Air Force Base, Oklahoma, where he was a T-38 flight commander and chief of the 71st Flying Training Wing's Operations and Training Division. His first staff assignment came in July 1975 when he joined the Air Training Command's Inspector General staff at Randolph Air Force Base, Texas. In October 1976, he became chief of the Air Space and Air Traffic Control Division for Air Traffic Control Division for Air Training Command.

From November 1978 to August 1983, he was assigned to Headquarters United States Air Forces in Europe at Ramstein Air Base, Germany. As a plans staff officer he was the overall program manager to U.S. Air Force F-16 conversions in Europe, specifically directing conversion activities at Hahn Air Base, Germany and Torrejon Air Base, Spain. He was also named chief of the Fighter Programs Division which had basing and other programming responsibilities for all U.S. Air Force fighter, reconnaissance and electronic warfare aircraft in Europe.

In August 1983, Colonel Baker was assigned back to Headquarters Air Training Command, Randolph Air Force Base, Texas as chief of the Readiness Division. He was directly responsible for the command's first combined command post and field training readiness exercise. He assumed this present command in October 1983.

The colonel is a command pilot with 4,000 flying hours in supersonic jet fighter and trainer aircraft. His military decorations and awards include the Distinguished Flying Cross, Meritorious Service Medal with two oak leaf clusters, Air Medal with four oak leaf clusters, Combat Readiness Medal, Vietnam Service Medel with three bronze service stars and the Republic of Vietnam Gallantry Cross with palm.

He was promoted to the grade of colonel on April 1, 1983 with the same date of rank.

Colonel Baker is married to the former Susan P. Bean from Big Spring, Texas. They have one son, Scott.

Brigadier General Pruden recommended that I stand up and beat the drum for an advanced instrument training course or IPIS. The IFC opened in October 1983 at Randolph. We work directly for the USAF and under AFR 23-2, and we are the focal point for instrument flight matters in the Air Force.

The IFC includes four divisions:

a. Flight Directives Division, responsible for flight publications and regulations.

b. Aeronautical Information Division, responsible for FLIP. The burning issue there is what to do with the F-16 and it's limited cockpit space. We're evaluating ways to shrink the FLIP and increase it's utility.

c. Instrument Procedures Division deals in the TERPs area, approach clearance criteria, waivers to nonstandard approaches and works with NATO in the ICAO arena.

d. Operational Plans Division (Lt Col Ercoline) which looks forward to anticipating the problems we'll be working in the future.

We do worry about instrument training. We're involved in it and write the 6-hour annual instrument refresher course.

We provide instrument training on the road to the ANG and AFRES.

We're monitoring ATC, and their plans to leave the T-46 essentially unchanged concerns us. It's a big transition from the round dial-T to the F-15, F-16 and B-1, and we feel the training should be upgraded with more modern displays to help bridge this step.

The old Instrument Pilot Instructor School (IPIS) put out experts to return to their units and serve as focal points on instrument related matters. There has been considerable interest out there to resurrect this, and we have attempted to reestablish some sort of advanced instrument training school. One proposal was for a 4-week course at Randolph AFB: 50 hours of academics, 7 hours of simulators, and 12 hours of actual aircraft flying as a final validation phase to prove to the pilot that it really works. We'd require a T-38 equipped with a HUD that could be programmed to display formats of either F-15 or F-16, whatever. Put the fighter pilots through one track using fighter-type displays.

On the TTB side, we'd use a T-39 or C-21, and eventually a follow-on TTB aircraft. In today's fast-moving world of instruments and displays, this would provide a core of instrument experts throughout the Air Force that could help keep the MAJCOMs up-to-date. I had a lot of support from CINCTAC and CINCSAC for a ground school but not for the flying program. There may have been some concern that it would just turn into a flying club. We estimated a cost of $6 million per year. In today's tight budget environment, it's difficult to get money to initiate new programs. We haven't given up; we'll keep punching.

PHYSIOLOGIC LIMITATIONS TO PILOT ATTITUDE AWARENESS

Mr. Terry Lutz
Arvin/Calspan Corporation
Buffalo, New York

BIOGRAPHY

Mr. Terry Lutz is an engineering test pilot for Calspan Corporation in Buffalo, New York where he is involved in flight control research. He served at the F-16 System Program Office during full scale development of the F-16, working primariily on the fly-by-wire flight control system. After spending one year as an acceptance pilot on the A-10 production program, he was selected to attend the USAF Test Pilot School. After graduation, he spent two years as Chief of Flying Qualities and Instructor Pilot of the Test Pilot School. He has over 3000 hours of flying time in various fighter/trainer aircraft including the F-4, A-10, A-7, F-15, F-16, Saab-Scania Viggen, and British Aerospace Hawk. His undergraduate study was at the University of Michigan and his Masters degree was earned at the University of Dayton. Both degrees are in Aerospace Engineering.

I guess I've had more time in some of those airplanes, but unfortunately a lot of them were just one time flights, but I was fortunate enough to be able to be exposed to the way they flew.

What I'd like to try to do in my presentation is pull together some of the things that we've already heard. I had put together a briefing that used some of Dave Milam's material, some of Dr. Malcolm's material and some of Pete Lovering's material, and then I talked to Grant and I said I've got this great outline. He says that's terrific and I said who else is speaking and he said, well Dave Milam is speaking, Pete Lovering's speaking and Dr. Malcolm, so what I did was I took some information that I had and tried to put it together into something that may plant some seeds in some minds here as to directions that we may need to go. I'm going to try and remain noncontroversial in the attitude indicator versus head-up display issue, if it is going to be an issue, and point out the big differences and let you make some decisions as to where to go. What I'd like to do is integrate some material that was developed by the Air National Guard, Major Milt Miller, at Tucson. Some of you may have read his article in Aviation Week. What he's done is put together a training program for teaching pilots to fly at very low altitudes and very high speeds, and he says this is what you can and cannot perceive with your human visual system. So what I'm going to do is integrate some of his techniques and show you how the rest of what we've heard in this conference can help us understand how to design the cockpit and how the pilot performs tasks in the cockpit.

Before we understand the physiological limitations to the pilot, we've got to understand who the pilot is, and it brings to mind a story that I heard that involved three surgeons at a medical conference: there was a German surgeon, a Japanese surgeon and an American surgeon--and they entered into a discussion about how easy it was to operate on people from their home country. The German said, "Obviously, a German patient is the easiest to operate on. First of all, they're engineered like they've engineered a Mercedes, everything fits, everything is in its proper place, you open them up, you find out that all the plumbing is on quick disconnects, from the German beer that they drink, everything is well lubricated, there's no problem to operate on a German patient." The Japanese man said, "No, I think the Japanese are far easier to operate on. First of all, they're highly reliable and you never have to open them up, but if you do happen to open them up, you find that all parts are very small, if you need spares you can get them easily, everything is cadmium plated; there is no problem to operate on a Japanese." The American doctor said, "Nope, I've got you both beat. The easiest person to operate on is the American fighter pilot. When you open a fighter pilot up, the first thing you notice he has no guts, second thing you notice is he has no heart, and at each end there's a moving part and they are both interchangeable."

Milt Miller has put together a real good low altitude training program. His objective is to look at the aerodynamics, physics, and visual limitations in that area and teach task-time-management. A real quick look then at current operational design trends in the cockpit. We've already seen the cross-check changes; we'll talk a bit about head-up display; I'll give you my interpretation of the differences between the HUD and the ADI as an instrument flight reference, and show you some examples of steps that the industry is taking in the right direction, and offer a few suggestions.

The other important message Milt gives involves the mission: the mission is why we fly the airplane. We want to take bombs to the target or take our gun and kill the enemy or missile and kill the enemy. Now in Milt's case, he's teaching low altitude flying training but he prioritizes it. He says what I want to do is teach low altitude maneuvering first. That's my first priority, and then the low altitude tactics. He wants to make avoiding the ground the most stable of all pilots' skills, so let's interpret that. What you're seeing is just like I'd train a pilot to fly good instruments in pilot training. Now I've got a pilot in the tactical environment, and I want him to wire up all those little circuits in his brain that teaches him to avoid the ground and places them on a subconscious level that becomes subconscious--he knows exactly where to look to get certain pieces of information when he needs it, depending on whether he's turning, straight and level or doing a vertical maneuver.

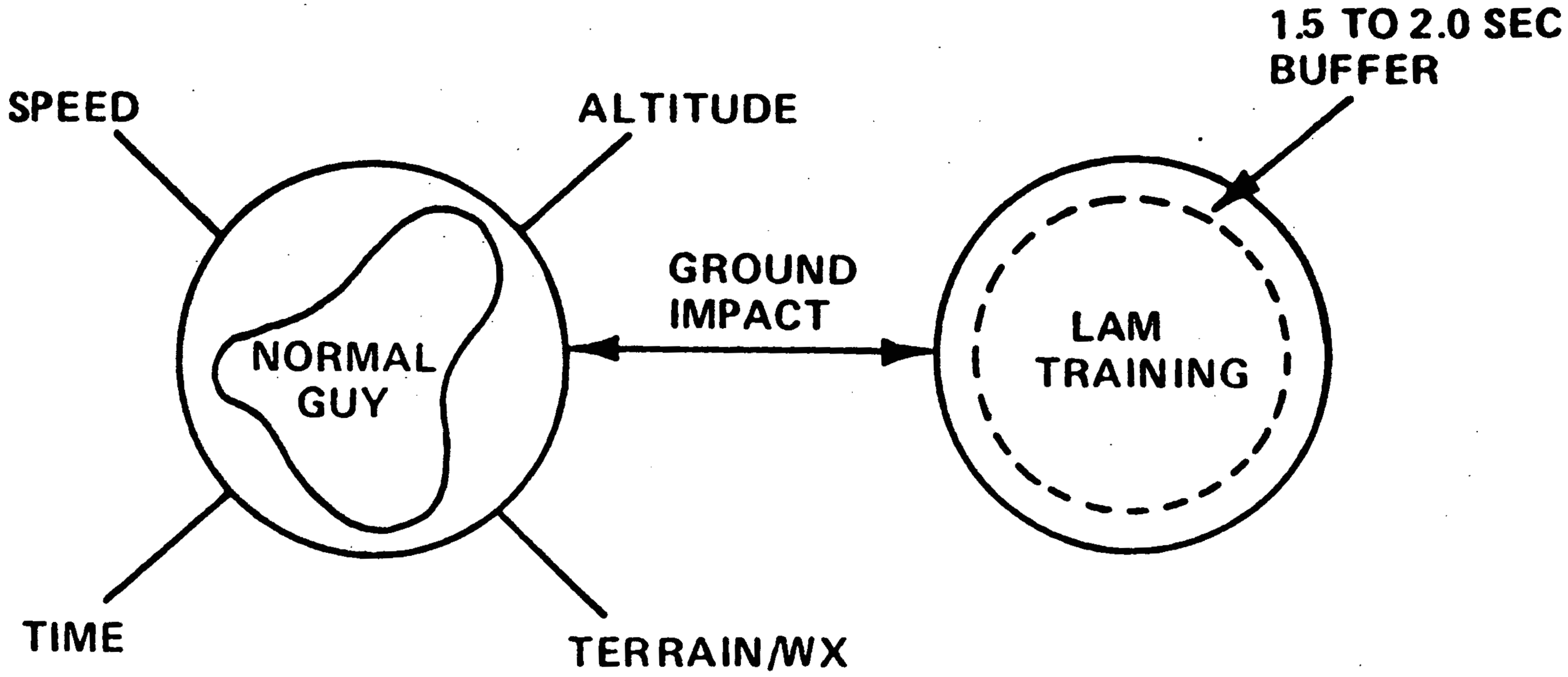
Every pilot has a personal ability right now to fly at low altitude (Figure 1). I know I do and I know some of the other pilots in this room do also. And depending on how fast you're flying, what altitudes you are required to fly, the terrain that you're flying over, the weather that you're flying through, and the amount of time that you have available to perform tasks in the cockpit or check your wingman or look for threats, you're going to give yourself a reactive buffer. But what Milt wants to do is say, "I want this guy to fly as low as possible and bring his capability right out here so he has a constant reactive buffer, depending on all those other conditions that he's flying." In other words, these areas in here are where he's increased his reactive buffer or where he cannot perform the mission quite as well or where the enemy can shoot him down easier if he gets him up in altitude. All right, so what Milt says is let's give the guy a 1.5-2.0 second reactive buffer between himself and the ground impact line which is the outer side of both of these circles, and he looks at the problem in terms of the aerodynamics, the physics and lastly the human perceptions.

Essentially when you fly at low altitude, you do it with three types of maneuvers (Figure 2). "You fly level flight for a majority of the mission, about 90 percent; you do vertical maneuvers about 3 percent of the time; and you do turning maneuvers about 5 percent of the time." Now, if you look at the visual capability of the pilot, which increases down this scale, and the sensitivity of the problem, (i.e. increasing sensitivity or the problem is getting worse for the pilot from an aerodynamics and a physics sensitivity standpoint) you find that vertical maneuvers fall in the middle between straight and level and turns; turns are the worst. What you want to be able to do is use your visual capability, understanding its given limitations, to improve the way that you do vertical maneuvers and to improve the way that you fly turning maneuvers at very low altitude.

This (Figure 3) is the aerodynamics and physics result and this essentially compares level flight in turns--you could do the same thing for a diving maneuver, but it's strictly the physics of the problem. If you entered a lo dive while flying at an indicated airspeed of 400 knots and your altitude were 500 ft, you'd have 35 seconds to ground impact; at 100 ft, 7 seconds. Now the way Milt calculated it: If you put a 1.5 second reaction time on here, in 7 seconds that would give you 5-1/2 seconds to recover; at that speed, you'd be able to bring 4 g's in within 2 seconds and the airplane's flight path would clear the ground by a slight margin, maybe 10-20 feet. Pretty benign in the straight and level condition, but if you go into a turn, your time to impact from 500', 300', and 100' are 7, 5 and 3 seconds respectively. Milt calculates the reaction time is about 50 percent of the time to impact; the reason is that the pilot must to recognize and roll out of a turn before he puts his 4 g's on in 2 seconds. Fifty percent of those reaction times are 3-1/2, 2-1/2 and 1-1/2 seconds which, of course, just happens to work out to be the same time at 100 feet.

LOW-ALTITUDE MANEUVERING

EXPAND EACH PILOT'S PERSONAL ABILITY



SPEED

ALTITUDE

NORMAL GUY

TIME

TERRAIN/WX

GROUND IMPACT

LAM TRAINING

1.5 TO 2.0 SEC BUFFER

LOOK AT THE PROBLEM IN TERMS OF AERODYNAMICS, PHYSICS, AND HUMAN PERCEPTIONS

Figure 1

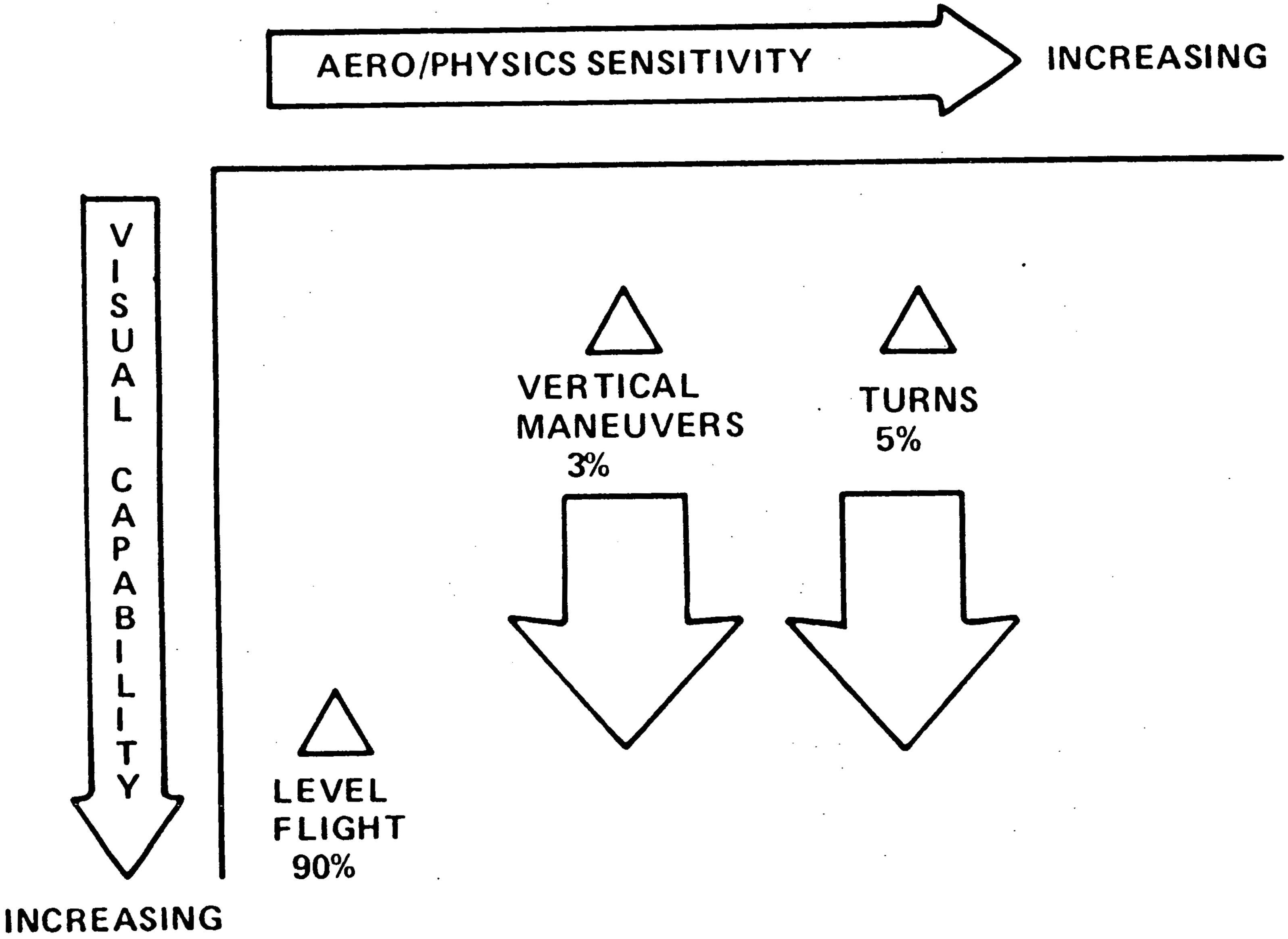

AERO/PHYSICS SENSITIVITY
INCREASING
VISUAL CAPABILITY
INCREASING
VERTICAL MANEUVERS 3%
TURNS 5%
LEVEL FLIGHT 90%

Figure 2

TIME TO IMPACT AT LOW ALTITUDE

1 DEGREE DIVE AT 480 KNOTS

ALTITUDE	LEVEL FLIGHT	4G TURN 10^{o} OVERBANK
500′	35 sec	7.0 sec
300′	21 sec	5.0 sec
100′	7 sec	3.0 sec

1.5 sec
REACTION
TIME

REACTION TIME
IS 50% OF TIME
TO IMPACT

Figure 3

That's the aerodynamics and the physics overlaid onto one slide for straight and level and for turning maneuvers. Now let's look at the visual capability of the pilot (Figure 4). There's a lot going on in what seems like a very simple slide. First of all, we saw a slide yesterday and one of the speakers alluded to the fact that we're all looking out through a set of goggles; and that's, in fact, true. We look out through a set of goggles which start peripherally. I can just barely see my fingertips now in my peripheral vision. It's about 180° field of view and then your central vision is right in the middle of it or wherever you happen to slew your central vision. Your central vision is about a 2° field, and if everything's working right, acuity is about 20/20. The acuity is peripheral vision field is almost 180o field of view, at least side-to-side; it's lower from vertically, and depending on the individual, it's about 20/400, so the acuity is not that high but you can pick up a lot in your peripheral vision. The significant thing about this slide is that when you pull g, maybe 4 g or depending on the person maybe that's 6 g's, but as you begin pulling g, the goggles begin to close down in size and you begin to grey out. Well, what exactly is that telling us? When you grey out, the mind is beginning to fill in your peripheral vision field of view with gray; it's strictly a constant gray input and it begins filling it centripitally. Now what else do you lose? If you could see in color in your peripheral vision, and we all do to some extent, (and I'm going to talk about that in a minute), you also lose color. It goes from color into gray. Now at whatever G-level that happens to be, you begin losing some of your peripheral vision. Your peripheral vision is becoming hypoxia, and if you are becoming slightly hypoxic, aren't there other brain processes that are beginning to slow down? Your hearing, your very, very fine perception of hearing is going to slow down just a little bit; if it is as sensitive a receptor as the eye, it will also be affected in the same manner. There may be some thought processes that are slowing down, too, so we need to be aware that in addition to having a visual limitation when we pull g's such as this, we ought to look into finding out what other degradations occur.

Let's put it into real time perspective. We all saw Nick Kehoe's videotape yesterday, and he says at the last part of the videotape that he lost his perception of where the horizon was. Well, we could all see that horizon easily. For an over the water flight, that was a pretty distinct horizon, I would say. I think that what happened is when he went to the merge and he went in for the hard turn, his peripheral vision shrank down to where he couldn't perceive the horizon anymore. Also keep in mind from hearing and viewing that videotape that the camera is looking straight ahead out the airplane; Nick Kehoe was looking over to his right or left for his adversary. He wasn't looking through the HUD; he didn't have the advantage of the attitude line. He's looking over to his right and pulling g's, so his peripheral vision shrinks down and now he's looking through a fairly small tube at his adversary. I believe that that's why he lost the perception of where the horizon was.

VISUAL ENVELOPE

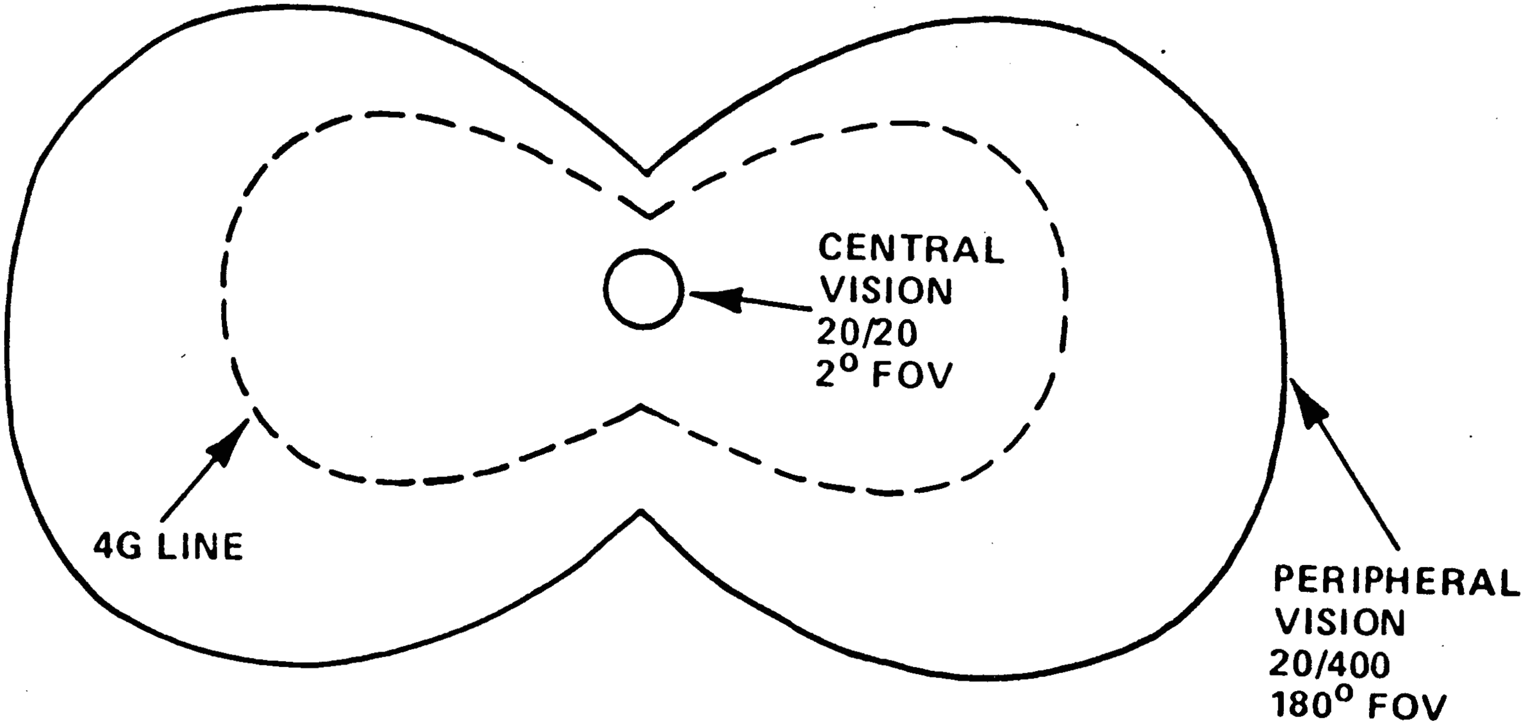


Figure 4

Three other slides on visual perception (Figures 5A & B). Your central vision is the conscious effort. It gathers information into discrete segments; it allows you to process information digitally so to speak. It measures aircraft parameters by direct viewing of instruments in the HUD. The central vision will not measure roll angle, it will not measure dive angle unless it has some other reference like the canopy bow or an instrument in the cockpit or the head-up display. It very accurately discriminates colors. It won't measure your velocity unless you read it; it won't measure flight path angle, pitch and roll attitude or range. You must use the HUD or other cockpit instruments.

On the other hand, with your peripheral vision (Figure 6), the subconscious effort, the information processing is continuous, and if we have time, Dr. Malcolm, I'd like to sit down and talk about whether your peripheral vision is one of these patched up, wired up things that you can improve through training or whether it's hardwired and always there, and what other things are hardwired and always there or need to be patched up and wired. But your peripheral vision provides what Milt Miller refers to as "speed rush baseline" and "speed rush conditioning". What that means is as you're flying along at 100 feet and 480 knots, you see the terrain whipping by at a certain rate and you become conditioned to that. If you happen to slow down at 200 feet to 200 knots from 480, you say, "Gee whiz, I could eat a sandwich here," because you were going so fast before and now you feel like you're going incredibly slow, when the fact is you're still actually doing 200 knots. Now for a fighter, that is kind of slow, but it is a wide speed range to which you are sensitive. It measures changes, the key word in that line is changes, in pitch and roll attitude. It won't measure them themselves but it would pick up the changes. If know where you were and you see the change in your peripheral vision, you'd know in which direction you're going. It is very sensitive to acceleration in terms of g and has limited color capability.

Let's talk for a minute about color (Figure 7). The information spectral density of a monochromatic display can be so great that it can overwhelm the observer. It's just what Pete Lovering told us in his briefing that I counted ten times the amount of information on this CRT than is normally shown on an attitude indicator. You can actually overwhelm the observer, and one way to pick up the ability to gain information off a display that has a lot of information on it is to use color in combination with pattern recognition. Some studies advise using only 4-6 colors maximum to avoid resaturating the guy from an information spectral density standpoint. There are limitations to color perception. Gray-out is loss of visual acuity and color perception. The second line here, if I had to rewrite it, I would rewrite it and say that in the peripheral vision, red seems to be right about in the center from about ±15o, and as you try to pick up things that are farther out in your field of view, the colors that are easiest to pick out change. They become somewhere, that's a contest in the literature, between blue and yellow out here at about 60o, so red may not be the best one except right in the center. The eye is differentially sensitive, as I mentioned; and symbols, when you're using a

VISUAL PERCEPTION

CENTRAL VISION (CONSCIOUS EFFORT)

- GATHERS INFORMATION IN DISCREET SEGMENTS
- MEASURES AIRCRAFT PARAMETERS BY DIRECT VIEWING OF INSTRUMENTS AND HUD
- DISCRIMINATES COLORS

WILL NOT MEASURE:

- VELOCITY
- FLIGHT PATH ANGLE
- PITCH AND ROLL ATTITUDE
- RANGE

PERIPHERAL VISION (SUBCONSCIOUS EFFORT)

- INFORMATION PROCESSING IS CONTINUOUS
- PROVIDES SPEED RUSH BASELINE AND SPEED RUSH CONDITIONING
- MEASURES CHANGES IN PITCH AND ROLL ATTITUDE
- VERY SENSITIVE TO ACCELERATION
- LIMITED COLOR CAPABILITY

Figure 5A

VISUAL PERCEPTION

CENTRAL VISION (CONSCIOUS EFFORT)

- GATHERS INFORMATION IN DISCREET SEGMENTS
- MEASURES AIRCRAFT PARAMETERS BY DIRECT VIEWING OF INSTRUMENTS AND HUD
- DISCRIMINATES COLORS

WILL NOT MEASURE:

- VELOCITY
- FLIGHT PATH ANGLE
- PITCH AND ROLL ATTITUDE
- RANGE

Figure 5B

VISUAL PERCEPTION

PERIPHERAL VISION (SUBCONSCIOUS EFFORT)

- — INFORMATION PROCESSING IS CONTINUOUS
- — PROVIDES SPEED RUSH BASELINE AND SPEED RUSH CONDITIONING
- — MEASURES CHANGES IN PITCH AND ROLL ATTITUDE
- — VERY SENSITIVE TO ACCELERATION
- — LIMITED COLOR CAPABILITY

Figure 6.

COLOR PERCEPTION

THE INFORMATION SPECTRAL DENSITYOF A MONOCHROMATIC CAN OVERWHELM THE OBSERVER

THE MOST RAPID DISPLAY INTERPRETATION IS WHEN COLOR AND PATTERN RECOGNITION ARE USED TOGETHER

USE 4 TO 6 COLOR MAXIMUM TO AVOID SATURATION PROBLEMS

LIMITATIONS

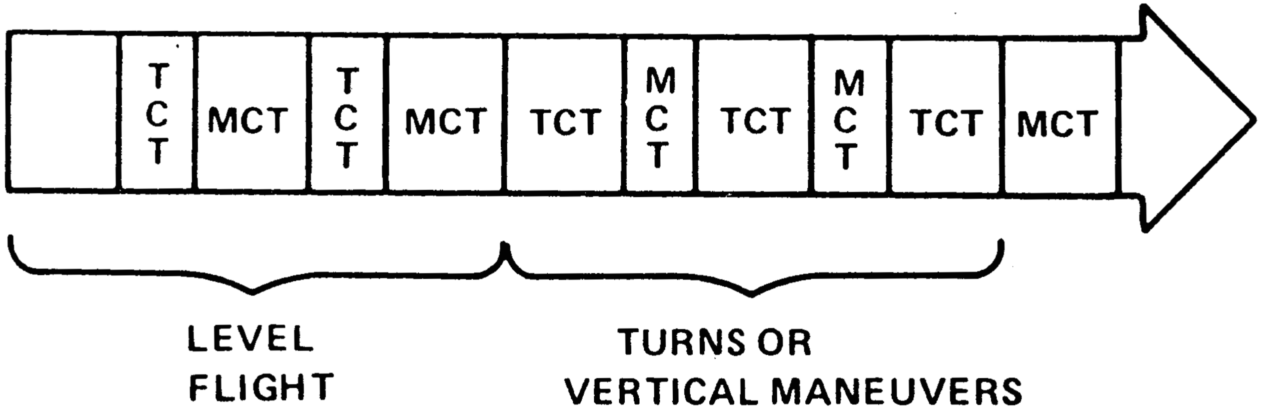
- GREY OUT IS BOTH LOSS OF VISUAL ACUITY AND COLOR PERCEPTION
- RED IS THE MOST DIFFICULT TO DETECT WITH PERIPHERAL VISION
- THE EYE IS DIFFERENTIALLY SENSITIVE TO COLOR IN THE PERIPHERAL
- SYMBOLS MUST BE SUFFICIENTLY LARGE TO AVOID SMALL FIELD TRITANOPIA

Figure 7

TASK-TIME MANAGEMENT

INTEGRATE THE AERO/PHYSICS LIMITATIONS WITH VISUAL LIMITATIONS

TCT – TERRAIN CLEARANCE TASK
MCT – MISSION CROSSCHECK TASK



*NEVER REDUCE TCT BELOW AERO/PHYSICS MINIMUM REACTION TIME

Figure 8

color display must be large enough to avoid a small field tritanopia, which is your inability to discriminate between the colors when the figures are very small.

What Milt does then is he says those are the visual limitations; when you recognize them you know that when you go into a vertical maneuver you have to look at some pitch attitude reference or pitch reference to tell what your pitch attitude is going up, rolling, inverting and bringing the airplane back down in a vertical or jinking maneuver. Your eye can't perceive that. If you go into a 30o dive, all you're looking at is dirt. Putting it on the other perspective, he was telling us of an accident which occurred while a guy was doing air-to-air maneuvers at very low altitude, and got into a very high sink rate situation. The only instrument in the cockpit that was moving, actually, was the altimeter. The airspeed was relatively constant because he was kind of stagnated; the vertical velocity was pegged at 6000 ft/min, the attitude of the airplane was slightly nose high and he was just sinking rapidly. The one thing that was important in that particular case was that if he had looked in the HUD, his velocity vector would have been caged in the bottom of the HUD, though, in fact, the velocity vector would have probably been down too because he was coming down rapidly or was in a turn at a very high sink rate. We need to recognize all those visual limitations and know what you can and can't perceive.

So he says those are the limitations, now how do you manage your time in the cockpit? Well this is what he says you should do (Figure 8). If you are going to avoid hitting the ground, spend some time on terrain clearance tasks. These are conscious efforts. And when you're in level flight, you don't have to spend very much time doing that; you can spend most of your time on mission cross-checks. But when you go into a turn or a vertical maneuver where from an aerodynamics and a physics standpoint the problem is much more difficult, you have to allot more time to terrain clearance tasking and less time to your mission cross-checks. Now, the idea is to go back to one of the first slides I showed and never reduce your terrain clearance tasking below the aerodynamics and physics minimum reaction time. Now, what this slide is really telling us, as airplane designers and airplane flyers, is that when we design an airplane or perform a task in the cockpit, we have to consider the amount of time it takes the pilot to do that individual task. If it's changing radio channels or if it's punching chaff, or if it's resetting his radar or resetting weapons switches, we need to be able to make those tasks simple enough and straightforward enough that he can do them and still have enough time to perform the tasks that he needs to, given his visual limitations, so that he won't hit the ground. Enough of the low altitude training program.

Let's talk a little bit about some of our current cockpit design trends (Figure 9). We've seen that we have gone away from the large, centrally located ADI and away from the T cross-check pattern, (I'll give you an example of that), toward the use of the HUD for all the flight parameters and toward

CURRENT OPERATIONAL AND DESIGN TRENDS

- AWAY FROM THE LARGE, CENTRALLY LOCATED ADI
- AWAY FROM THE "T" CROSSCHECK PATTERN
- TOWARD USE OF THE HUD FOR ALL FLIGHT PARAMETERS
- TOWARD THE USE OF THE UP FRONT CONTROLS AND MULTI-FUNCTION DISPLAYS

*THESE ARE DISTINCT MODIFICATIONS TO THE WAY PILOTS ARE TRAINED TO PROCESS INFORMATION

Figure 2

the use of up-front controls and multi-function displays. These are big modifications to the way pilots are trained to process information. We heard a lot of talk yesterday about training, and I think it was good talk, and we need to discuss what we can do from a training standpoint to teach guys to handle the new cockpits.

In the F-15 (Figure 10), (I'm sure that the guys from McDonnell-Douglas that are going to speak are going to give us some more information on some of the subjects I'm going to briefly touch on here), there's a nice T cross-check pattern. The attitude indicator in the F-15, centrally located, is the larger size and a pilot can be able to look from side-to-side in the cockpit at different things and be able to keep that attitude indicator there in his peripheral vision. If I take the attitude indicator and put it down here and look up to here, it's farther away from my central vision field of view and farther out in my peripheral vision. The information that we heard yesterday said that the size of a given object or figure must enlarge as you get further out in your peripheral visual fields in order to be able to perceive it. So if you take our attitude indicator and move it down in our field of view, it has to remain fairly large or it has to grow in order for him to be able to perceive it in the same way.

Here's the F-15E (Figure 11), same airplane, newer version. Now the cross-check pattern hasn't been established for this airplane yet and there are two ways that it can go. You can either bring your attitude indicator down here in the center MFD, and cross-check up to say a radar display here on the right MFD, and an E-square display here on the left MFD, or whatever happens to be on the menu; or you can fly the airplane primarily in the HUD and cross-check down. I don't think that's been established yet, and I think that's something that TAC needs to take a long, hard look at and see which way we're going to cross-check instruments in this airplane. Now the McDonnell guys are going to tell us that you can bring the attitude indicator up on any of these displays and that's fine and that attitude indicator will work. It's 3" in diameter, and it works just like the mechanical ADI. But as far as cockpit management and time management for the pilot, I think it's the user that's going to have to decide how he wants to manage his information flow in the cockpit.

A brief look at head-up displays. This is the A-7 head-up display (Figure 12). You'll notice that the A-7 is one of the earliest HUDs that the Air Force used if not the earliest, and it tends to be in an analog format both for airspeed and altitude with digits to highlight things. It has a digital heading format here. The only one difference that I could see about the A-7 was that they tended to use very clear and slightly larger characters for some of the pitch information and some of the heading information, but other than that, it's the only difference that I could find.

F-15A/B/C/D CROSSCHECK PATTERN

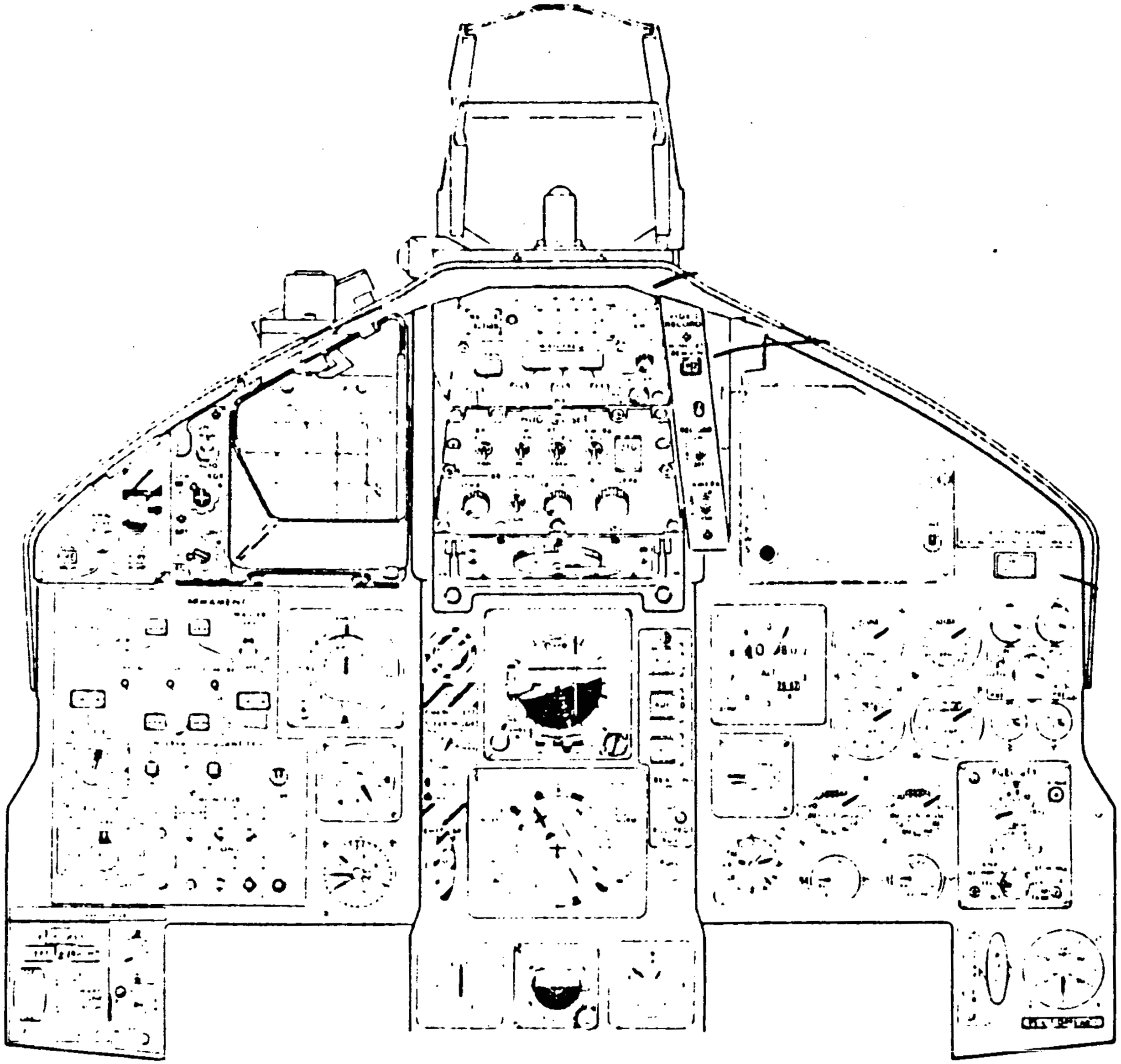


Figure 10

F-15E CROSSCHECK PATTERN

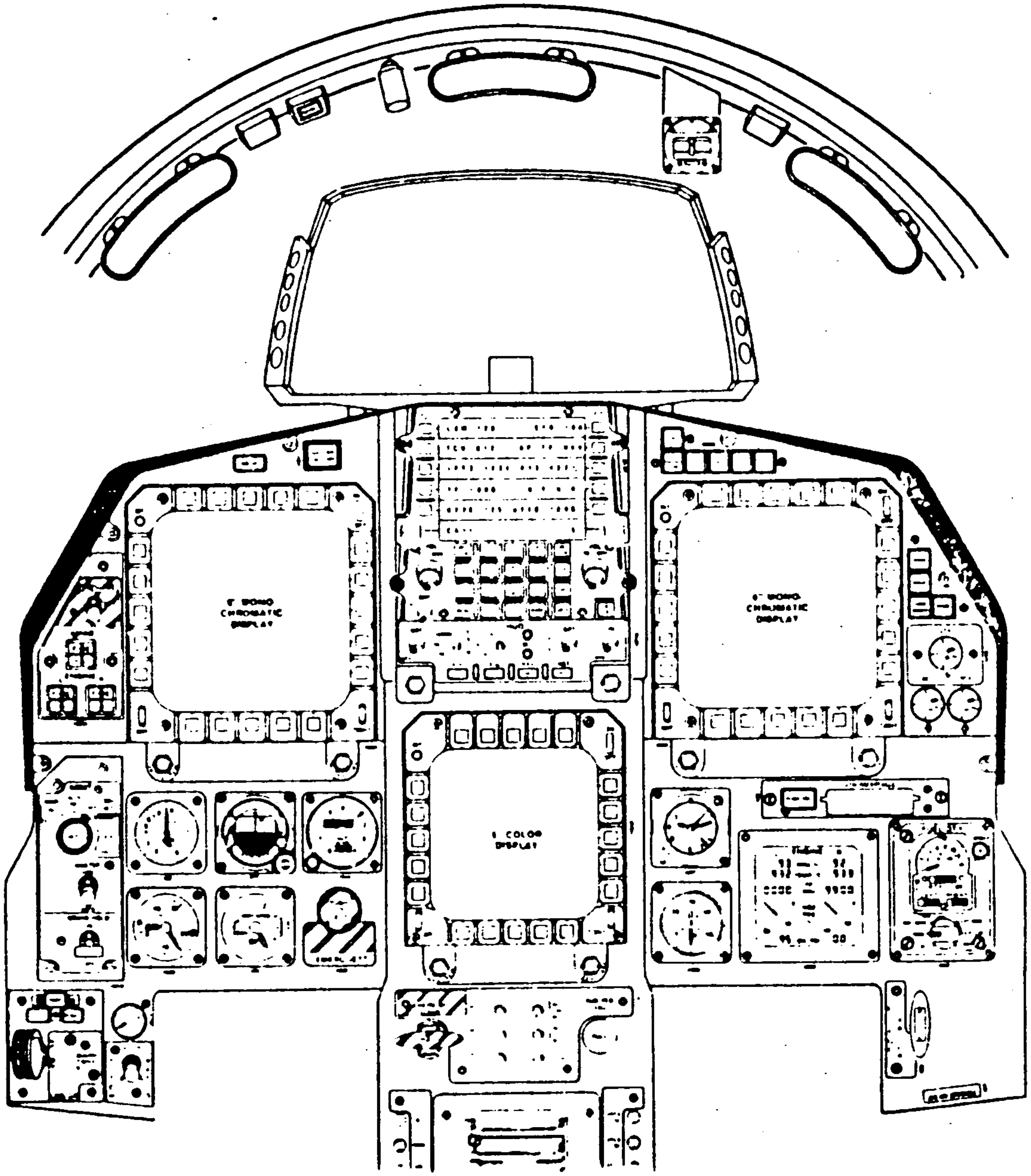


Figure 11

A-7D HEAD UP DISPLAY

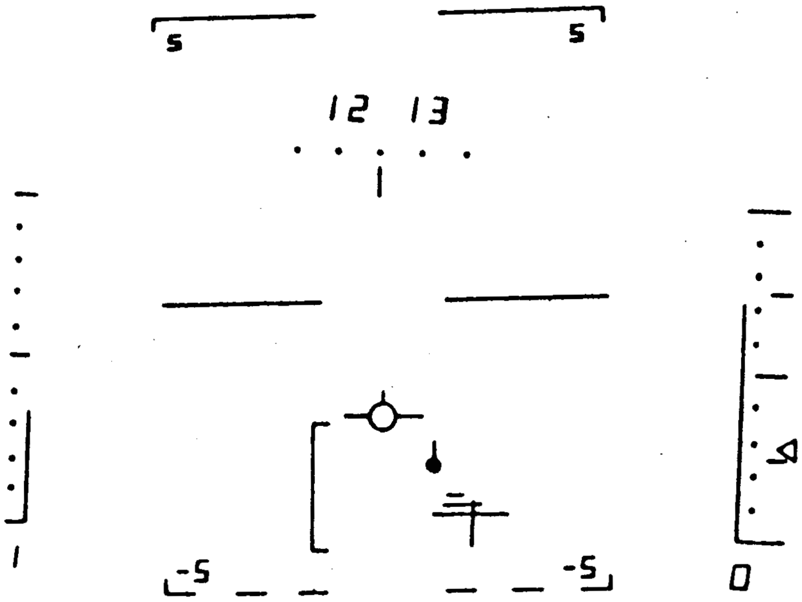


Figure 12

Now I have made a box here in orange and this box is very similar to the little box that Pete Lovering showed you with the overlay, and I'm going to show it on an attitude indicator. This box is approximately, however it goes, it actually goes a little bit higher than that and a little bit lower than that, it's more ladder shaped than it is box shaped, but I'm going to show you what that looks like on an attitude indicator and one slide more.

This is the F-15E head-up display (Figure 13). Now the F-15E head-up display is a definite improvement over some of the other HUDs we've had, mainly because of the declutter. The reason I asked Pete the question about the sky pointer versus the earth pointer is because they have selected an earth pointer to give the pilot bank angle information in the head-up display. They've also gone from an analog or thermometer format for the airspeed and altitude scales to strictly digital. It's cleaned up the HUD a little bit and I think that's kind of a step in the right direction, but we can still do more.

Now, before I leave this particular slide and go to a slide showing the electronic attitude indicator that's in the F-15E, I'd like to say that to me, the difference between an attitude indicator and flying on the HUD is that they command things in a different way. When you're flying an airplane and pull back on the stick and you're looking at the attitude indicator, it's an attitude command system; the pilot and the airplane are together in an attitude command loop. When you fly the airplane with a head-up display and you use the velocity vector, it's a velocity vector command system; pull back on the stick and the velocity vector begins to move. Those are not interchangeable. We've spent a lot of time training pilots to understand the attitude display; let's train them now to to understand the velocity vector display. It has limitations like caging itself in very high rate maneuvers. Also, the pitch ladder smears and becomes unreadable in very high pitch or roll rates. We need to know when he can and when he can't use it, what the differences are, and give the guy a set of tools that he can put in his tool box that's every bit as strong and every bit as commanding as what he's using today for the attitude indicator.

This is the electronic attitude display in the F-15E (Figure 14). (I put that little window that I outlined on the A-7 HUD in there so you get an idea that the window to the world from a head-up display is smaller than the window to the world from an attitude indicator.) Now, what we need to do is examine the information that we put in that little window and make it useful for the pilot. A guy like Joe Bill Dryden who has flown a lot with head-up displays, has wired up the paths and he knows how to put those things together so that he can use the HUD to the maximum advantage. We need to be able to find out what those tools are and begin wiring them up in some of our pilots' minds. Dave Milam made some good comments yesterday about the ideal athlete who does things strictly naturally, and if you ask him to describe how he does it, he says no, I don't really want to talk about it because he may not have thought about it in that incredible detail. But I would like to defer Dave's

F-15E HUD

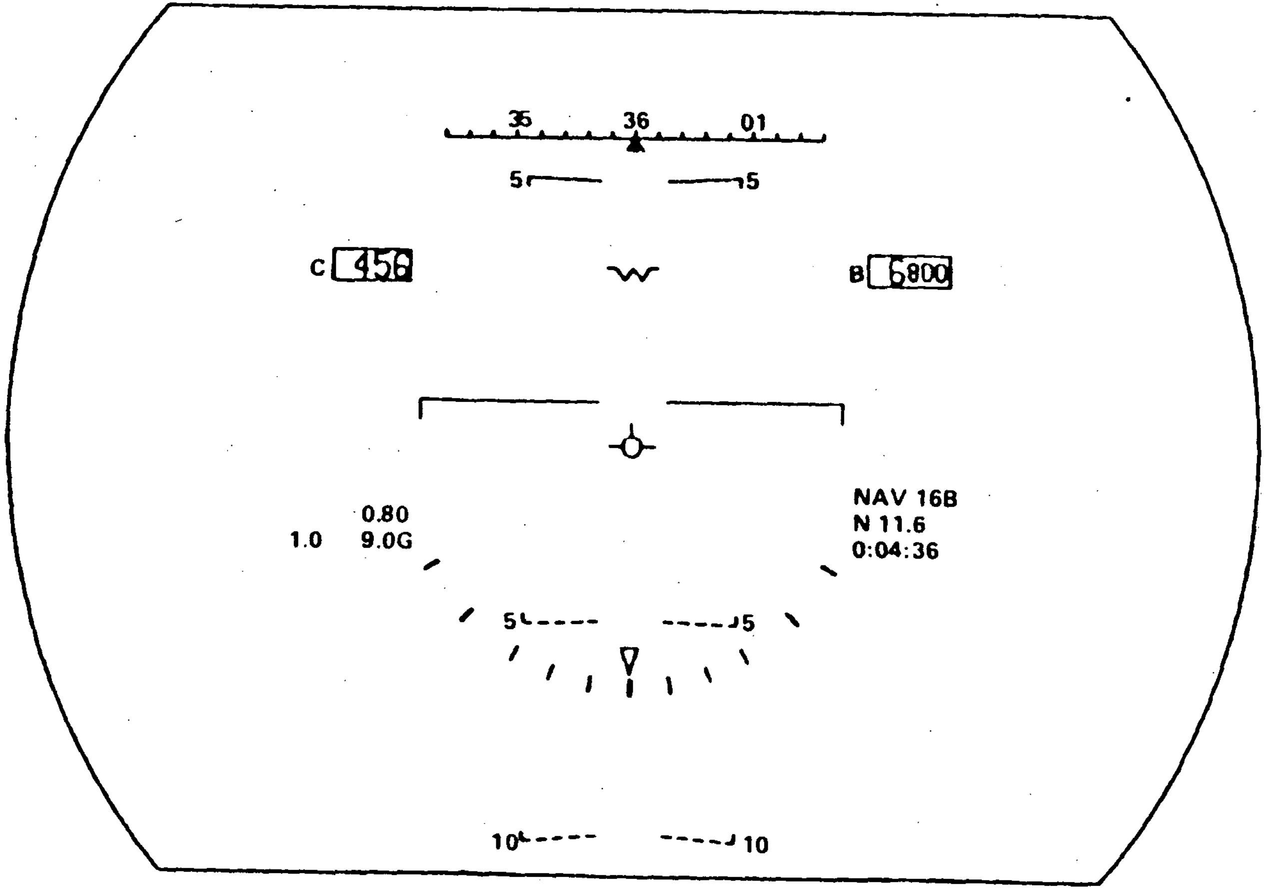


Figure 13

F-15E ELECTRONIC ATTITUDE DISPLAY

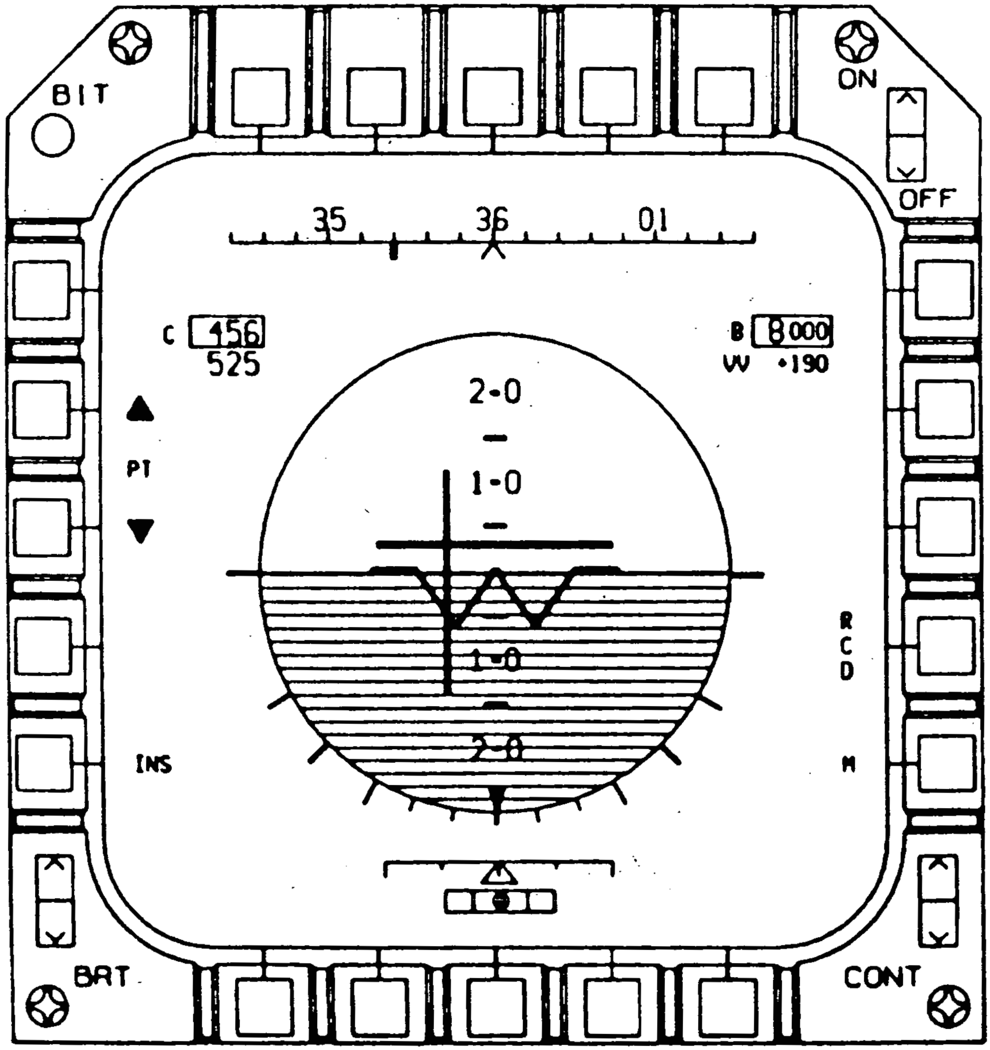


Figure 14

F-15E HEAD UP DISPLAY

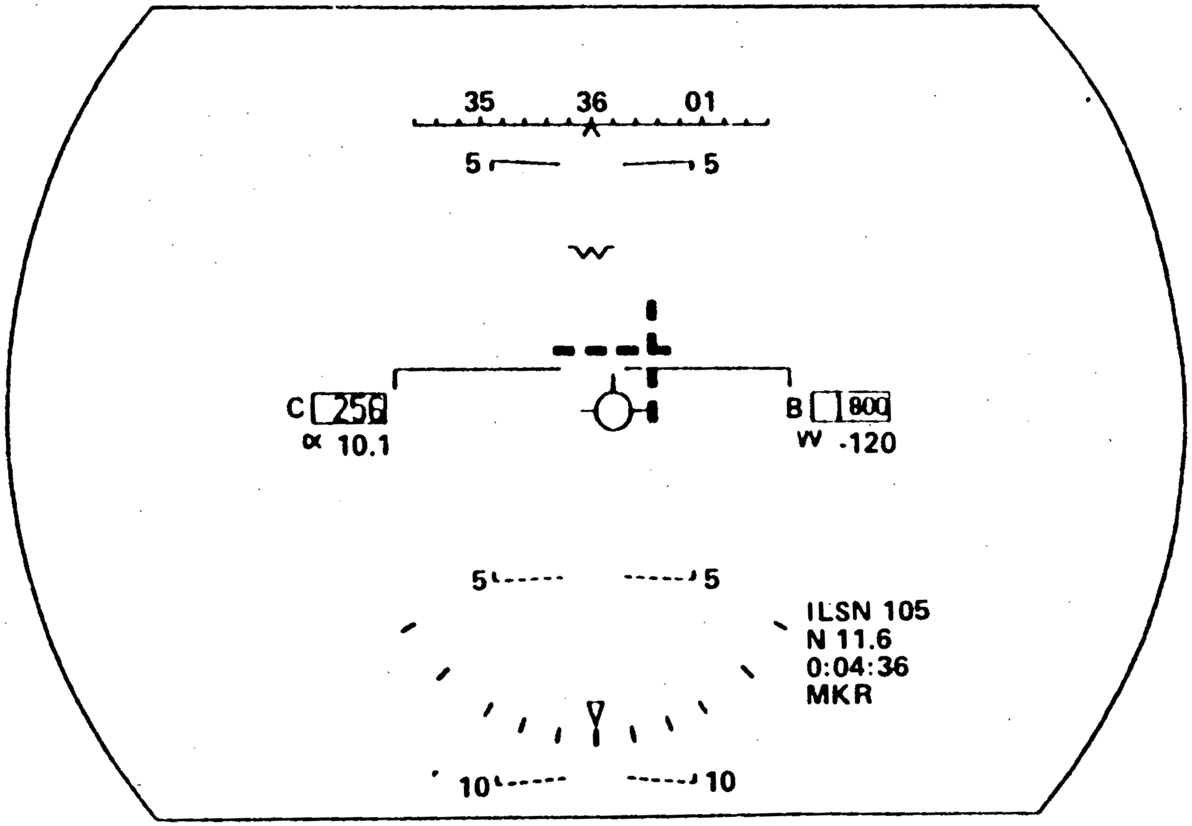


Figure 15

statements to the fact that when he was trying to teach those fighter pilots to use the L-COS (Lead Computing Optical Sight) after only 15 minutes in the F-16, he had to pick apart the task of firing on the dart into minute detail and explain it to that pilot before he could put him in the airplane and make him successful. I think that if Dave sat down or if Joe Bill sat down and put on paper and began to analyze what it is they're doing when they're flying with the head-up display, they'd be able to come up with a clear and accurate description of what they're actually doing. It's not easy, but it can be done. And that's in fact what we need to do to teach that information and pass that information on to other people.

Okay, a couple other things that are being done that I think are in the right direction, this is in addition to the F-15E head-up display (Figure 15). Those of you who have flown the F-16 know that in the early days they had strictly raw ILS data coming up on the HUD, and the guy said, "No, we want flight directed data up there", so it was changed to put flight directed data up there. Well, McDonnell has come up with a plan where they put both command information and displacement information in one display. The vertical and horizontal bars are your bank and pitch steering bar and the breaks in the bars indicate how many dots you are off the ILS course or off the ILS glide slope. Sometimes it's difficult to figure it out and then it'll pop. I won't leave it up that long, but it is a good display and a step in the right direction.

Another thing that they've done on the F-15E. This is an E-squared terrain following display (Figure 16). Those of us who have used air-to-air radars know that on some portions of the air-to-air radar display, the horizon line of the airplane is displayed (left upper corner, Figure 16). But what they've done in addition to showing where the radar sweep is in this little portion, they've shown the pitch and the bank steering bars for the terrain following radar overlaid with the horizon line so the pilot can actually see while he's checking his E-squared scope that's right there in his peripheral vision in the upper left corner. It's actually not too bad.

Some summaries and suggestions (Figure 17): From Milt Miller's training, he calculates that the time to ground impact for a pilot is fixed by the aerodynamics and the physics nature of a given situation. What you need to do is give the pilot the tools or let him understand his visual limitations so that he always creates and maintains a reactive buffer. Now the time required to do that is limited by the efficiency of the information receptors. I talked mainly today about the eyes, but the ears and seat of the pants are also information paths. How efficiently we use those paths indicates how efficient the pilot can maintain his reactive buffer. It's also dependent upon the degree to which the subconscious functions have been established, and if you want to read into that <u>training</u>, that's probably a good way to do it, but what I really mean is that he needs to look at <u>every individual little task</u> and patch those things up so eventually he performs these tasks on the subconscious level.

F-15E E^2 TERRAIN FOLLOWING DISPLAY

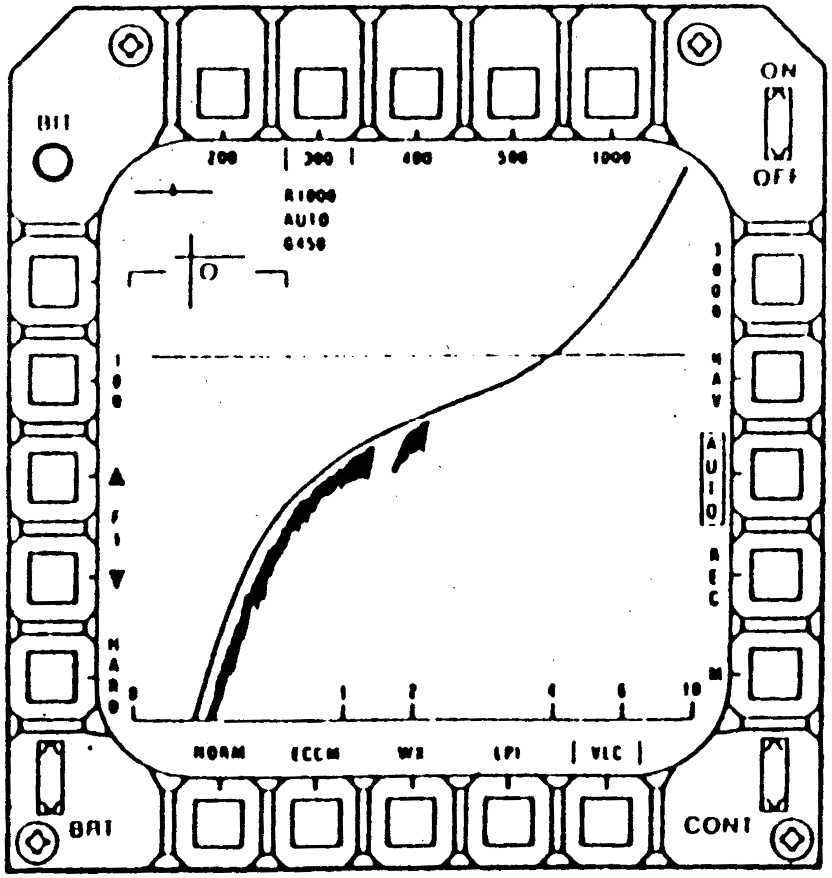


Figure 16

SUMMARY

TIME TO GROUND IMPACT IS FIXED BY THE AERO/PHYSICS NATURE OF A GIVEN SITUATION

THE PILOT MUST CREATE AND MAINTAIN A REACTIVE BUFFER

TIME REQUIRED TO DO THIS IS LIMITED BY

- EFFICIENCY OF INFORMATION RECEPTORS (EYES, EARS, SEAT OF THE PANTS)
- EFFICIENCY OF THE INFORMATION FORMAT
- DEGREE TO WHICH SUBCONSCIOUS FUNCTIONS HAVE BEEN ESTABLISHED

SOME CURRENT DESIGNS HAVE INCREASED THE TIME REQUIRED TO MAINTAIN THE REACTIVE BUFFER

Figure 17

SUGGESTIONS

- EXPAND TRAINING TO MORE EFFECTIVELY USE EXISTING SYSTEMS WITHIN PERCEPTUAL LIMITS

BRING THE HUD INTO THE ATC CURRICULUM

CONTINUE HUD DEVELOPMENT AT IFC

EXAMINE NEW DESIGNS FROM TWO STANDPOINTS

1. TIME REQUIRED TO PERFORM RANDOM TASK SERIES (CONSCIOUS EFFORTS)
2. POSSIBLE SUBCONSCIOUS SKILL TASK DEVELOPMENT

RESEARCH AND INTEGRATE ALTERNATE INFORMATION PATHS

AIRPLANE TO PILOT

AND

PILOT TO AIRPLANE

Figure 18

Now, this last line can be read two ways. Some current designs have increased the time required to maintain the reactive buffer because they're not as efficient from a cross-check standpoint; or you can read it - some current designs have decreased the time available to maintain the reactive buffer because the pilot is so tasked-saturated or the mission is very task-dependent.

Now, these may be over on the apple pie side, like Dave said yesterday, but we really need to do our homework and expand training on how pilots fly instrument tasks, primarily on HUD displays, and also within our own perceptual limits (Figure 18). I think it's mandatory now that the HUD be brought into the ATC curriculum, and I don't say that we need to put HUDs in all the T-38's or T-46's; we can start today by putting a HUD in a simulator or putting it just on a TV screen and say, okay, this is how this works, this is how that works, this is the limitation, you're going to see it in the future, lock that into core memory. That starts the ball rolling; it starts people into thinking, "I'm going to be using the head-up display sometime; these are the limitations, and this is how I'm going to use it, if and when I have to use it."

I think that we need to continue our HUD development. There are improvements on the way. I think there are other ways that we can improve the head-up display. That little bitty window to the world that we have can display one heck of a lot of information; let's make sure it's the right information and the most efficient information for a pilot. And let's look at our new designs from two standpoints: The time required to perform a random task series, i.e., the time that's required to do these conscious efforts--I'm going to change my radio channels now, I'm going to punch chaff; I'm going to look over here at my wingman or I'm going to reset my radar or I'm going to check the menu over here on the multi-function display. How long does it take the pilot to do that because if it takes him an excessive amount of time and he's at 100 ft at 480 knots, he might have a ground impact because he's spending more time on that and less time on his reactive buffer.

Let's look into what of those tasks can be put on the subconscious level, either by putting something in the airplane like the Malcolm horizon where he brings attitude information in through the peripheral vision, or other tasks. What else can he get or can he use on the subconscious level, and then let's look at alternate information paths. Let's look at what we can and can't do from a recognition standpoint with our ears and what we can and can't do from a tactile standpoint. The F-16 and the F-15 airplanes by design have neutral speed stability, you don't feel the change in airspeed or the requirement to trim as the airplane changes in airspeed. We need to be able to give the pilot some other cue that tells him that he's rapidly changing airspeed without having to look in the cockpit or look at the HUD and focus on that thing. Is it increasing or decreasing and how much is it, and when am I going to be over a limit, or when am I going to be in trouble getting too slow?

Finally, let's see if there are any alternate command paths. We definitely don't want to put buffet into the airplane because we got rid of that, and it was one of the good things that we did from a tactile standpoint. Let's look at airplane to pilot and also pilot to airplane. The AFTI airplane has done things with voice command that can reduce the amount of time that it takes the pilot to perform a task. For example, if I'm flying an air-to-air engagement and I want to know fuel, I'll say, "Fuel," and the airplane will either bring it up onto the HUD or say, "2800 lbs," or something like that, so that you don't have to look--you can keep your eyes out there on your adversary or you can pay attention to avoiding the terrain and maintaining your reactive buffer. Thank you.

MULTI-FUNCTION DISPLAY VS THE DEDICATED ADI

Paul I. Summers

McDonnell Aircraft Company

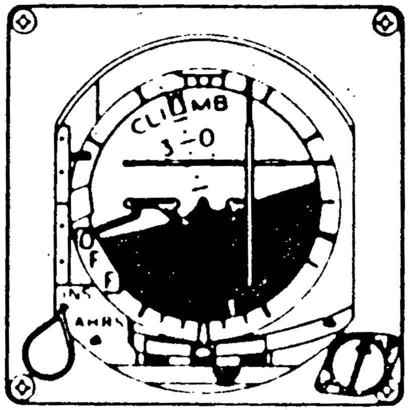
BIOGRAPHY

Mr. Paul I. Summers joined McDonnell Douglas in 1976 after receiving his B.S.E.E. in 1971, attending Air Force Officers Training School, Undergraduate Pilot Training in 1972, and working on the A6E TRAM for Grumman Aerospace Corporation through 1976. Mr. Summers subsequently worked on F/A-18A avionics weapon system integration for 5 years, followed by 3 years in Mac Air's Advanced Design Division, studying developments in advanced crew station technology. For the last 2 years, Mr. Summers has been assigned to Mac Air's ATF project, concentrating on crew station controls and displays, as well as weapon system integration activities.

Mr. Summers is also a pilot in the Illinois Air National Guard with over 3000 flight hours. He is currently flying the A-37 Dragonfly at Peoria.

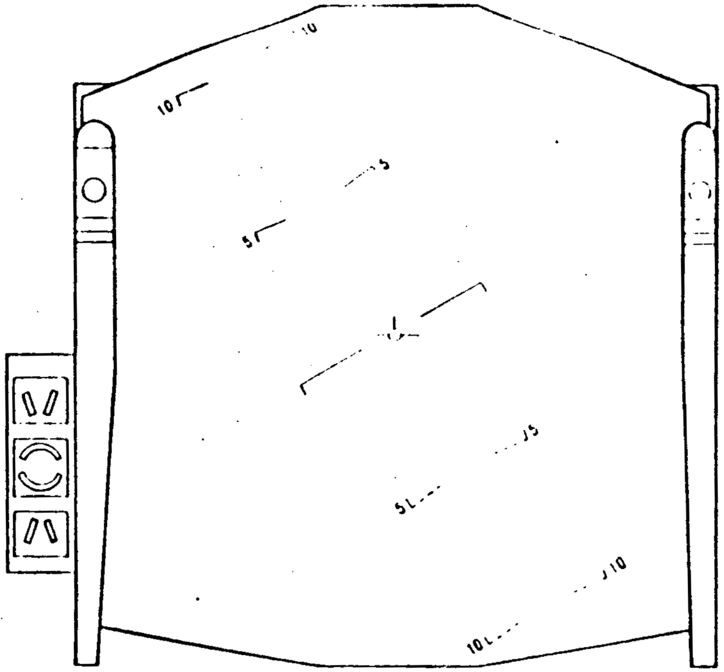
Well, good morning. I have heard a lot about the standard instrument this morning. You know, its kind of interesting; in the A-37 we have what we call the standard instrument W, which stands for, "It's a complete Waste of time to fly in the weather." I don't know who designed that. Is there anybody here from Cessna, by the way? I also enjoyed Mr. Lutz's pitch from Calspan. I was wondering if they have any viewgraphs I can use. Sounded like a big advertisement from Mac Air. Basically the subject for today is the dedicated ADI versus the MFD (Figure 1) and you'll notice that it's a HUD and not a classic interpretation of the MFD (Multi Function Display). In essence, I define an MFD as any display medium in the crew station that you can use for multiple uses and a HUD indeed can be used for multiple uses for many different things. I would like to discuss a little of the history of displays and we have dwelled in this conference a great deal on history. I think that's fine and wonderful but I'm here to tell you I'm here to take you to the future. Talk a little about current approaches, primarily the F-18, and what we think the future holds. Col McNaughton discussed about what the ingredients are for attitude awareness and I couldn't agree more except that I would include vertical velocity (Figure 2); I think that it is very important to establish what your rates are, in addition to all the other parameters. These are the things, the sources if you will, that I consider essential for attitude awareness.

ADI



VS

MFD



- **History of Attitude Displays**
- **Current Approaches**
- **What the Future Holds**

Paul Summers
McDonnell Aircraft Co.
St. Louis, Missouri

GPS1 004

Figure 1

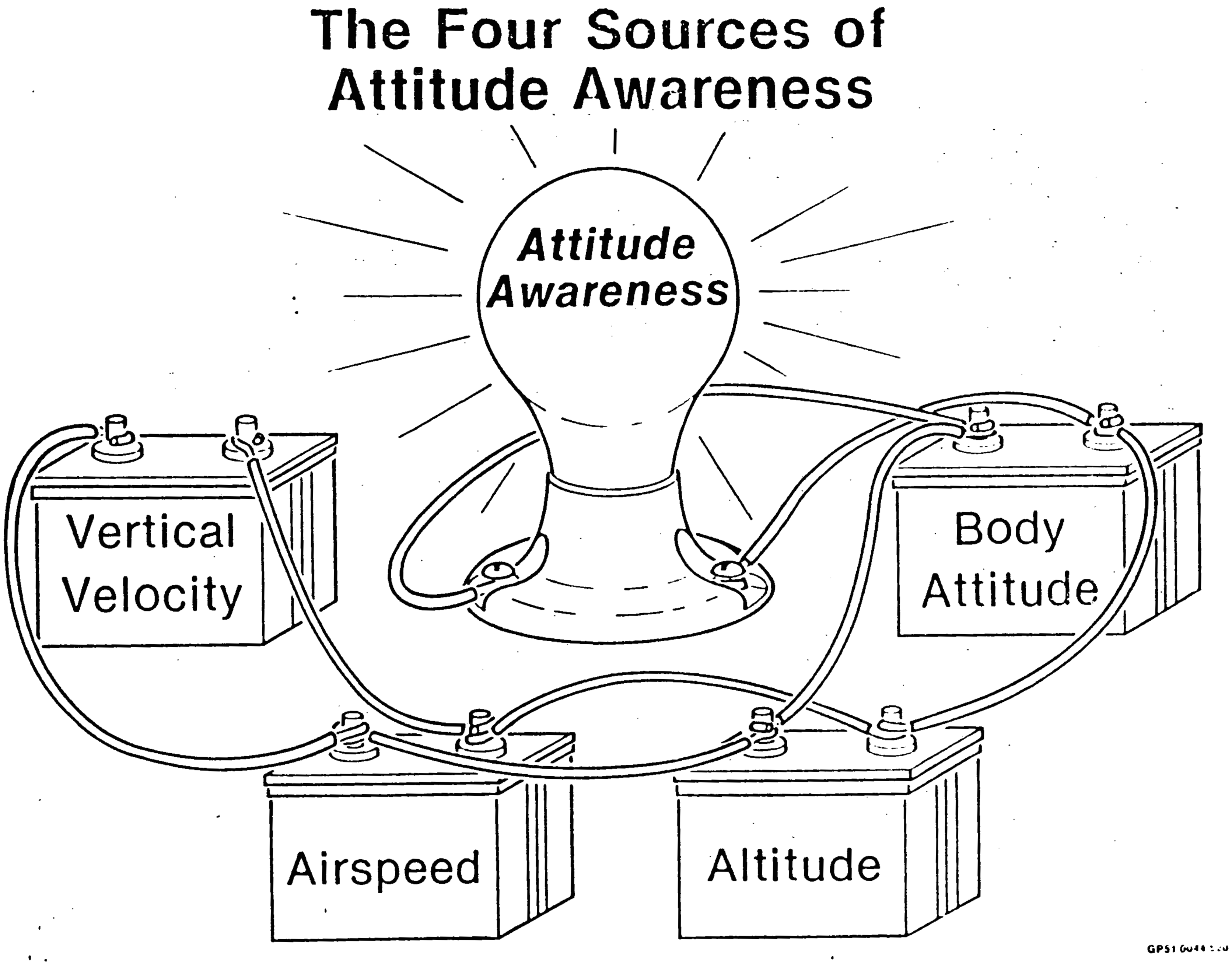

The Four Sources of Attitude Awareness
Attitude Awareness
Vertical Velocity
Body Attitude
Airspeed
Altitude
GPS1 0044

Figure 2

P-51 Mustang Cockpit

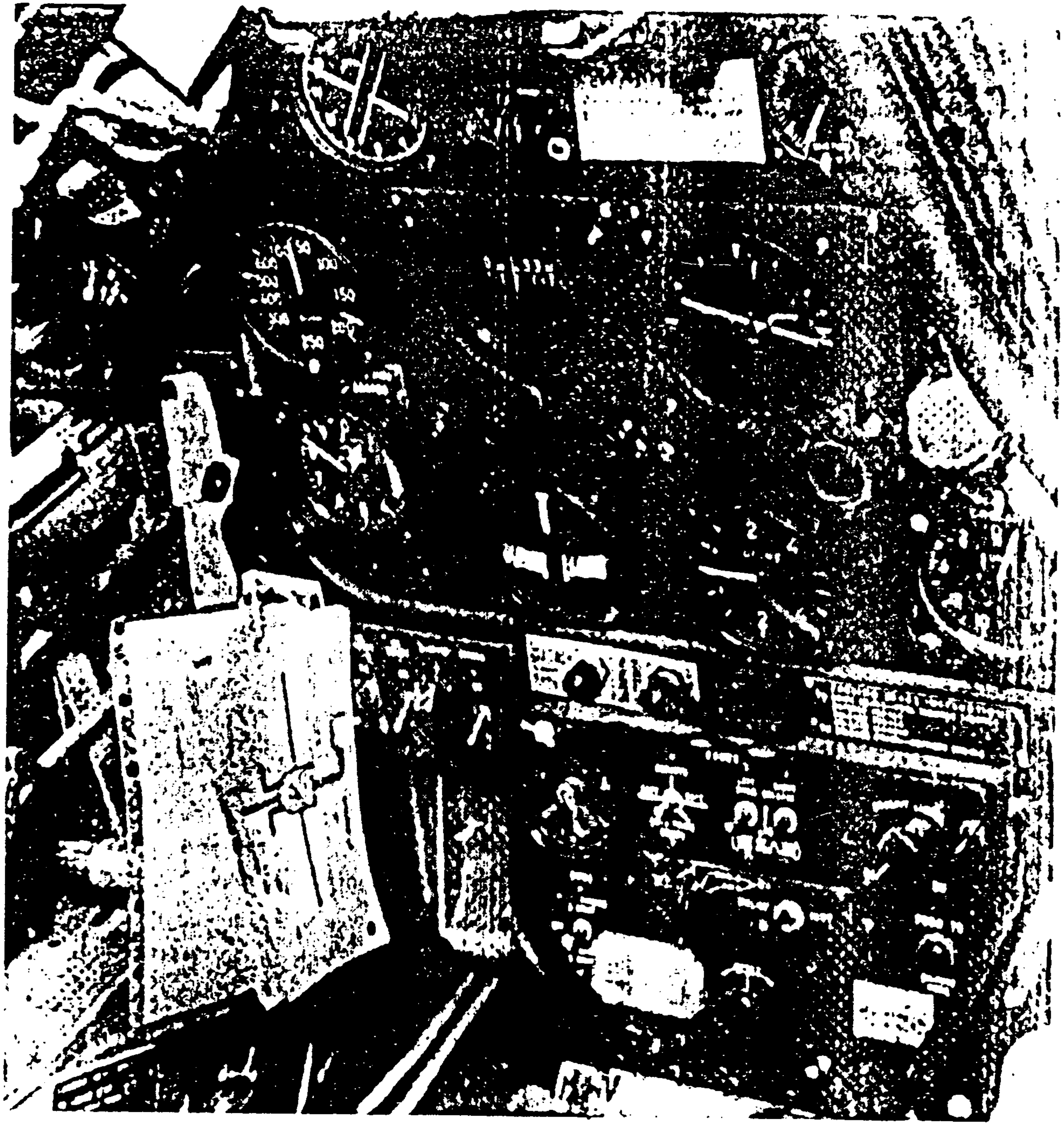


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Figure 3

In the past a lot of work has been done, and believe it or not, this is the crew station for the Spirit of St. Louis. I think this is an attitude indicator. It had air speed, altitude, a clock, and a periscope, and that was about it. This is the P-51 (Figure 3); it looks pretty sophisticated, but 70% of that crew station was dedicated to the attitude awareness parameters. Non variable--they were fixed. Is General Pruden here by the way? He wanted this slide. This is the F-4 (Figure 4). First flew in 1952 time frame. It is really a conglomeration of steam gauges and round dials. It is really very difficult to see out the front of the airplane. I don't know if any of you have ever seen this airplane, but basically attitude awareness instrumentation consumes 20% of the instrument panel. That is a lot to dedicate to that function. It requires the pilot to look down and in to determine his outside world situation.

Some of the historical obstacles to attitude awareness/MFD type of approaches. (Figure 5): Historically CRTs or whatever display medium you were talking about had insufficient brightness at 10000 foot lamberts ambience. That has gone away; that is no longer a problem. The argument was that tactical aircraft and trainers should have similar equipment. We have talked about that and, frankly, if we wait for ATC to get a modern airplane, we're going to be flying round gauges for ever.

CRT failure rates: right now they are actually better than electro-mechanical displays. Understandability of attitude information: no demonstrated MFD attitude display could match the understandability of the ADI presentation.

The design goals for current fighters are to increase the tactical flexibility of the main instrument panel by using MFD's and to offload most attitude awareness and visual attack functions to the HUD (Figure 6). The F-18 is a small airplane which has about half the instrument panel area available to it as an A-7. Yet it had multi-mission requirements. Now how do we solve that problem? We have to make the instrument panel extremely flexible. And the goal is to offload most of the attitude awareness and visual attack functions to head up. To those of you who are not familiar with what a F-18 looks like, this is a picture of it on its first flight. And this is a basic outline of its crew station (Figure 7). Basically what it attempted to do was to take all the things that were typically on the console and all the things that require dedicated switches and dials and round gauges and integrate them into multi functions. It's got a head up display as a primary flight instrument in the F-18. The Navy has adopted the HUD as a primary flight instrument. It has 3 CRTs, multi function displays, all 5 x 5, currently monochromatic, there is an ECP going on to make them color. The center part is an upfront control, which I am sure you are aware of. This particular up front control handles all the communications, navigation, identification, and weapons programming functions. He never has to look down on the console. As a matter of fact, if you look at the consoles they are fairly sparse. We also included the moving map display in the crew station

Fighter Crew Station

F-4 (Phantom)

Attitude Awareness Information

- Consumes ≃20% of Dedicated Main Instrument Panel Space
- Requires the Pilot to Look "Down and·In" to Determine His "Outside" Situation

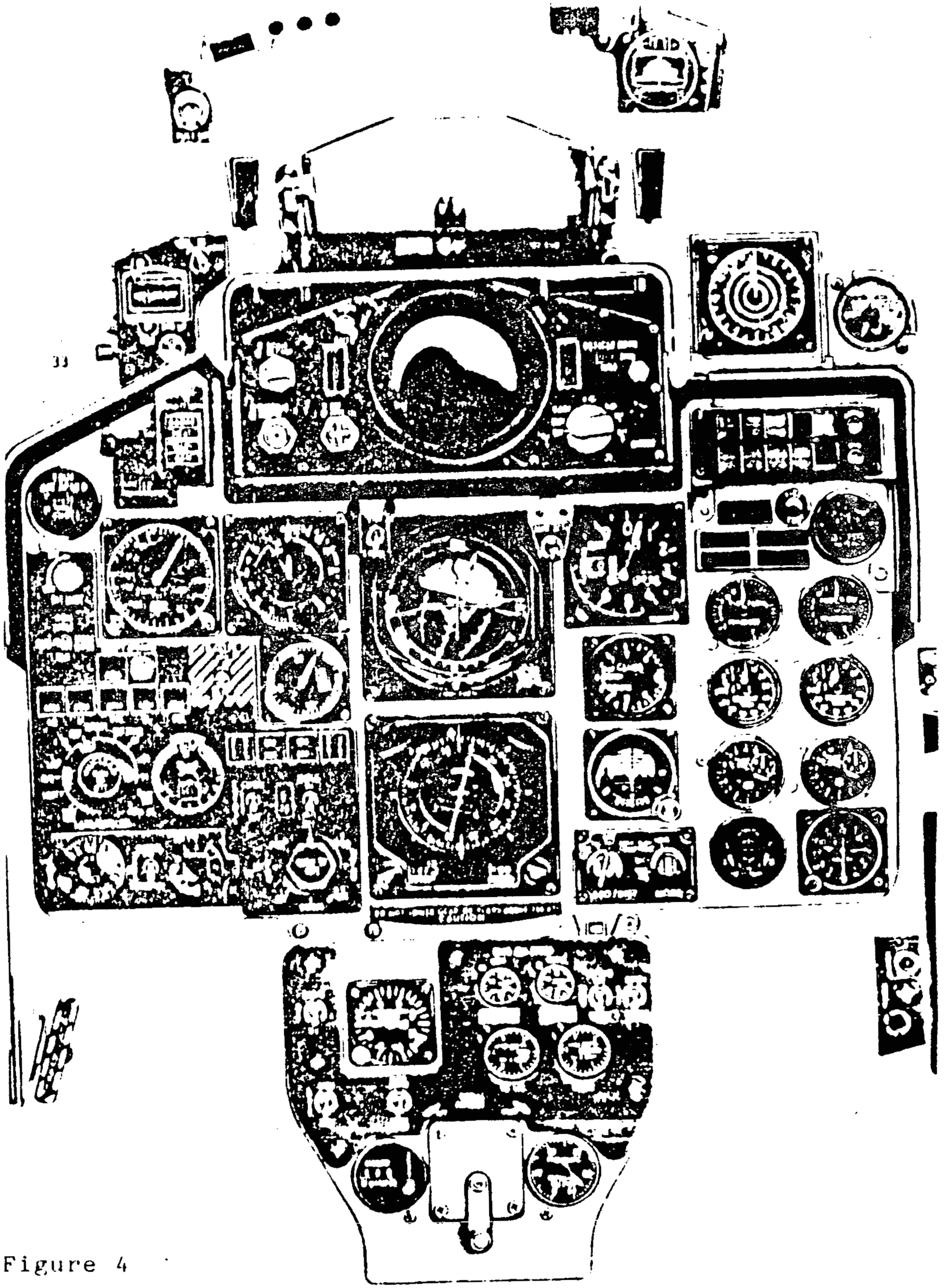

Figure 4

FRONT COCKPIT F-4E

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Historical Obstacles to MFD Attitude Awareness Displays

- Insufficient Brightness
- Tactical Aircraft and Trainers Should Have Similar Equipment
- CRT Failure Rates
- No Demonstrated MFD Attitude Display Could Match the Understandability of the ADI Presentation

GPS1 0044 523

Figure 5

The Design Goals for Current Fighters

- Increase the Tactical Flexibility of the Main Instrument Panel by Using Multifunction Displays
- Offload Most Attitude Awareness and Visual Attack Functions to the HUD

GPS1 0044 [illegible]

Figure 6

F/A-18A COCKPIT MAIN INSTRUMENT PANEL

INHERENT FLEXIBILITY

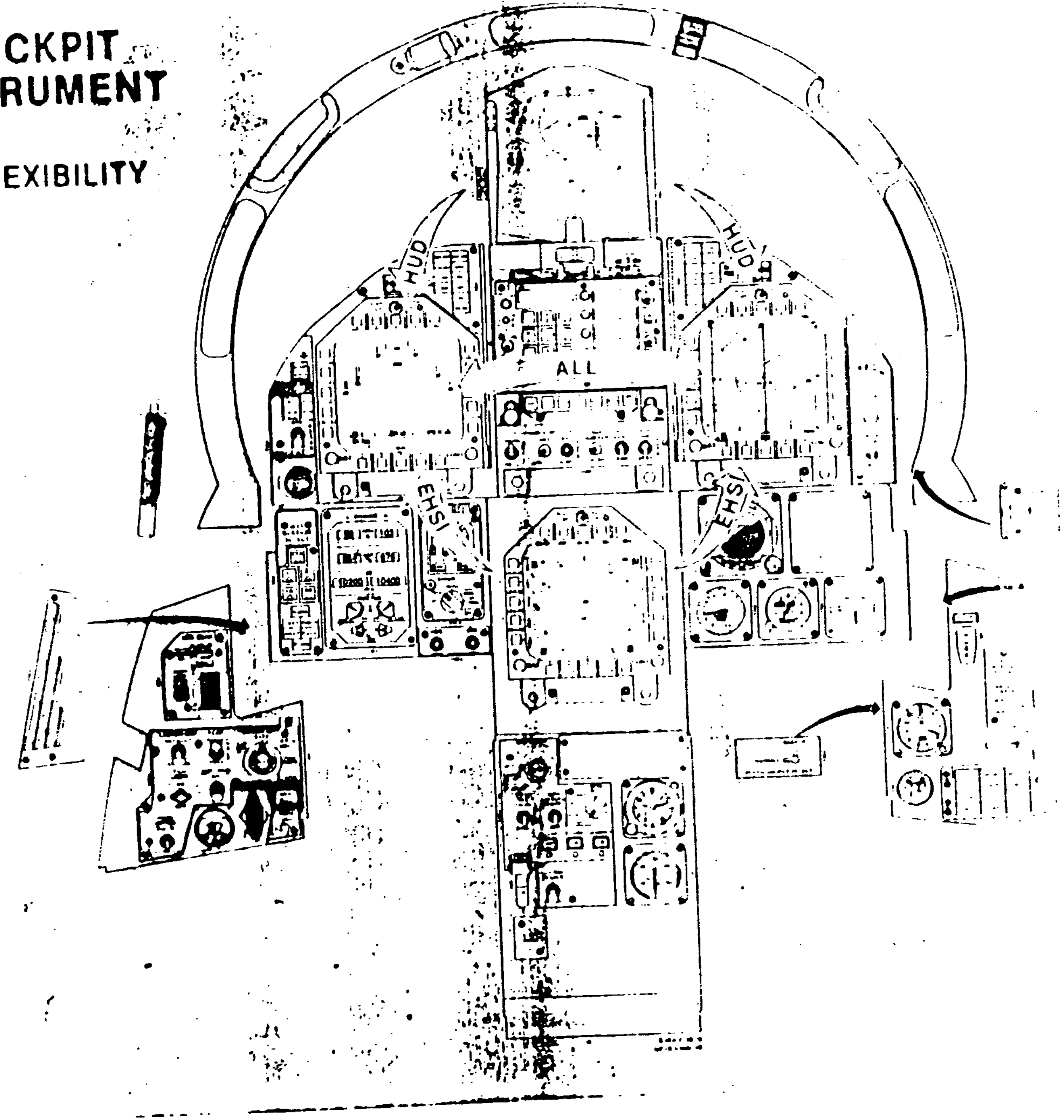

Figure 7

F/A-18A Navigation HUD Display

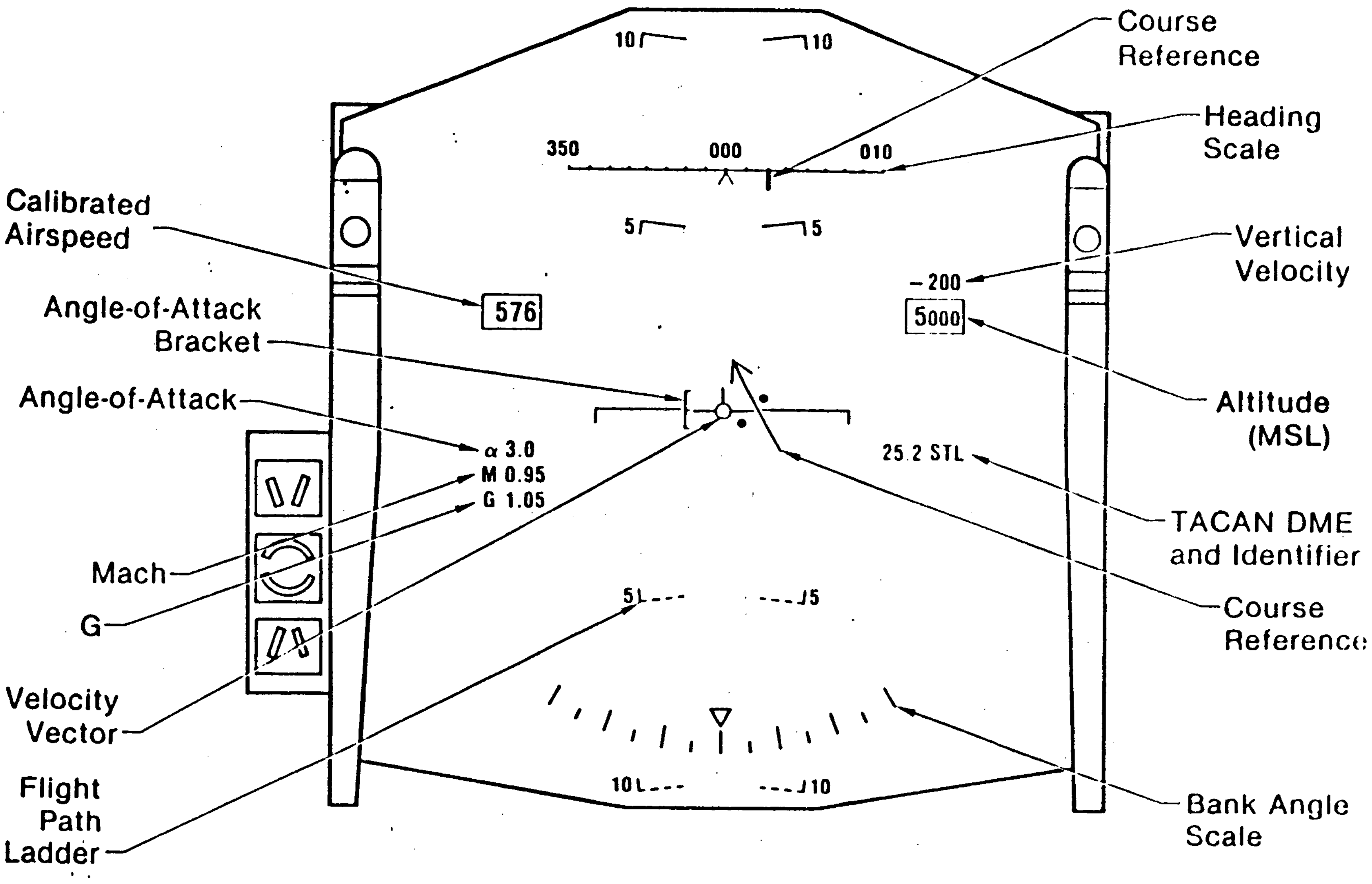

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Figure 8

for the air-to-ground mode.

There is a standby cadre of instrumentation here; frankly, it is very difficult to use because of its location. The inherent flexibility of the crew station is this: the electronic HSI information can be brought up on either tube; any of the weapons or sensors can be brought and displayed on any tube, and the HUD information can be brought down and put wherever you want. So if you are flying through the clouds and you do get vertigo, you simply put your HUD down on the tube and I'll show you some data later that indicates that most pilots fly with the HUD on one of the tubes almost continuously.

This is a typical navigation HUD on the F-18 (Figure 8) and we've gone through that so now it's self explanatory. Some of the key features that were mentioned before include the digital information in lieu of the scales and needles. There is considerable inertia to overcome to get that digital information in there. The F-15 has scales. The problem with scales is they're a large light output, that they consume a great deal of the HUD and they obscure a great deal of the vision plane. People complained initially about the digits not giving trend information. Recently I haven't heard a bad word about it. So I think a lot has to do with acclimation and accommodation. You can learn to fly it.

Some of the features we put into the F-18 were previously mentioned. Because the HUD is indeed the primary flight instrument we had to put some changes into the HUD symbology to accommodate the unusual attitude situations, and one of them is what we call the vectored flight path, which you've seen (Figure 9). Basically we use solid and dashed flight path lines to indicate above and below the horizon, respectively. Now, the F-18 is capable of very high pitch rates. This makes it impossible for the user to read where he's at so what we do is we angle the pitch ladders at one half the flight path angle. So essentially when he is at 60 degrees flight path angle, the pitch rungs are angled to 30 degrees and they always point to the horizon. It gives you the accordion effect. So you always know exactly where the horizon is. I have a brief video tape showing that in the loop, so if you'll bear with me I'll turn it on.

(From the video)

As the flight path angle increases, the ladder angle becomes greater. Presently the aircraft is pointing staight up, or at the zenith; and coming down the back side of the loop the angle decreases. As the loop continues and the flight path gets below the horizon, the flight path ladder is segmented. Going straight down the nadir symbol is a cross on the display; pulling on up towards the horizon, the ladder angle continues to reduce. (End of video)

Now there are some other additions required to make this truly an attitude display. They call this a slide feature (Figure 10). As you recall

F/A-18 HUD

Vectored Flight Path Ladder

Angled Flight Path Ladder Shows

- Solid and Dashed Flight Path Lines Indicate Above and Below the Horizon
- High Pitch Rate Trend Data
- Always Points to the Horizon

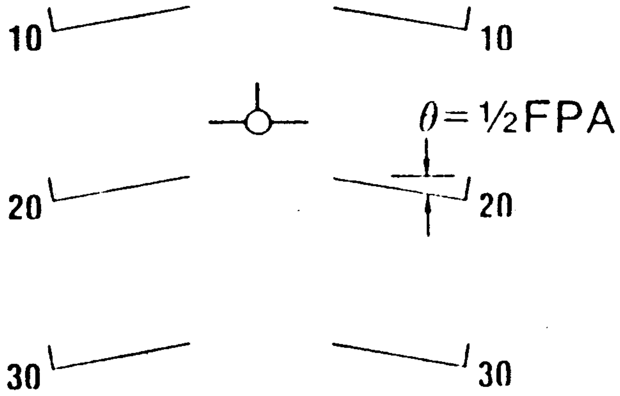

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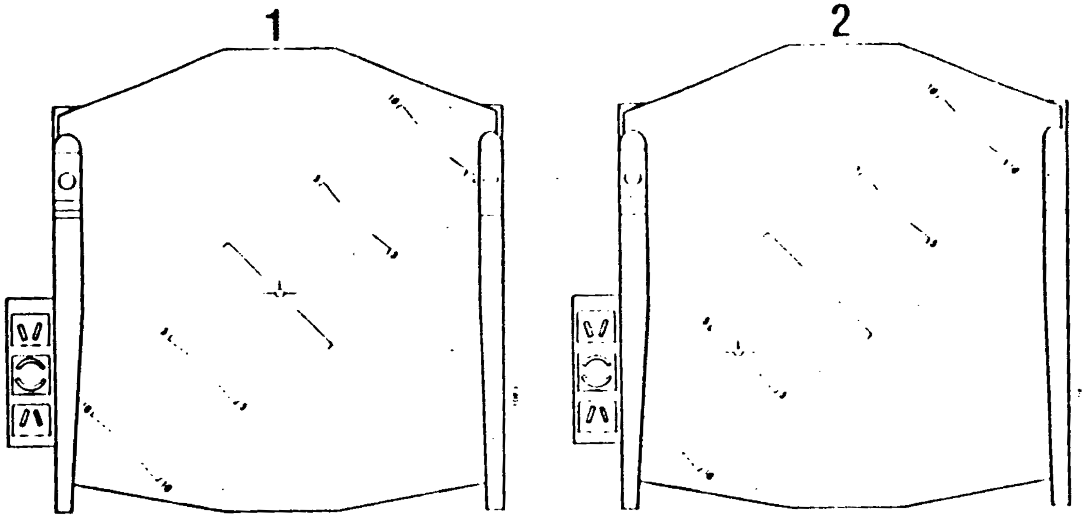
Figure 9

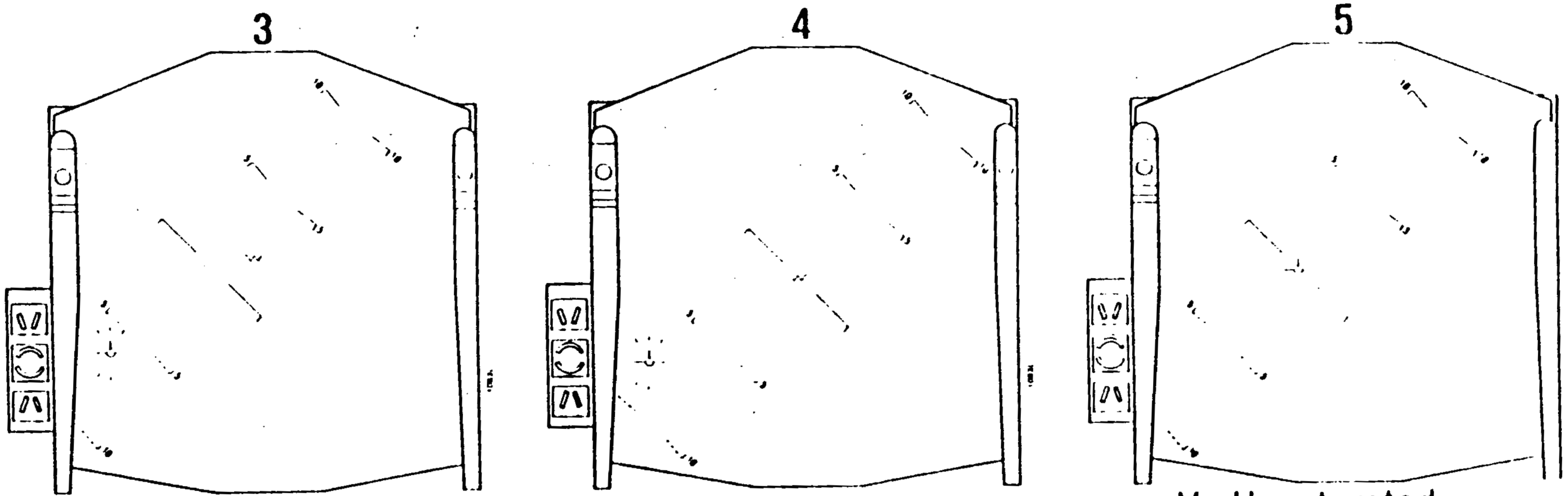
F/A-18A HUD
Slide Feature

- **Designed to Supply Valid Attitude in Large Angle of Attack Situations**



- 45° Left Bank

- α Increasing



- V_V Saturated
- Pitch Reference Appears

- Flight Path Ladder Becomes Pitch Ladder

- V_V Unsaturated
- Pitch Ladder Becomes Flight Path Ladder

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Figure 10

in the video tape and has been discussed before, the velocity vector, because it shows you where the aircraft is really going, has a tendency to slew over the HUD as the aircraft direction changes. As you attain high angle of attack or sideslip situations, the velocity vector has a tendency to saturate or cage in the HUD FOV, and historically the flight path ladder, which followed the velocity vector, and your attitude information would essentially disappear. What we've done, if you can follow through this, is number 1 shows a velocity vector centered in the HUD with a 45 degree left bank. Now as the pilot starts to pull back on the stick, he starts to increase his angle of attack. You can think of it from the center of the HUD to the center of the velocity vector is indeed the true angle of attack. As he continues to pull back, the AOA increases, until the velocity vector is caged and starts to flash in the corner of the HUD. At that point we bring up what we call the water line symbol which is essentially an attitude reference just like an ADI ball. And what happens is that the flight path ladder transitions and integrates over to the water line symbol and locks into it. So you are seeing essentially ADI information while your velocity vector is caged. As soon as your velocity vector, your angle of attack decreases to the point where your velocity vector comes off the cage, the pitch ladder now again becomes a flight path ladder by sliding back in and locking back into the velocity vectory, and the water line symbol disappears.

Now subsequent to that design, we put what we call the cage feature into the F-18. What that allows you to do is to cage the velocity vector at any point in time to the center of the HUD and make it a pitch reference instead of a velocity vector reference, so if you're in DACT or air combat maneuvering, you really don't need to know where your velocity vector reference is, you can keep it caged all the time. It becomes important in landing, when you want to put the velocity vector in essence right on the point you want to touch down on. So we have all these features that enhance the HUD's applicability to become the primary flight instrument. We realize that in a cosmic airplane the pilot is going to be spending a lot of his time head down. So we've put attitude information essentially on almost every display, head down as well. So when he's working his air-to-air radar, the attitude information is available. When he is working air-to-ground, again, attitude information is available.

If he's working forward looking infrared (FLIR), again, attitude information is available and becomes even more important when you have an infrared with large gimbal limits like we do in the F-18. They use the infrared to track a target as they fly over the target; the infrared scans and keeps stabilized on that target and it actually goes behind the aircraft to give the pilot BDA. We found that when he looked at that he got a tumbling sensation, if he didn't have the attitude display right on the FLIR. Putting it there seemed to have solved the problem. And as I mentioned, you can get a vertigo-inducing situation in and out of cloud. You can put the attitude display right on the VDI. (Vertical Display Indicator). And for the field grade officers, it displays a 3" diameter colored ADI ball, computer-generated, on the 5" MFD.

Now we were extremely concerned about how this was going over. Was the HUD working as the primary flight instrument, what was it used for? So we did a very detailed survey in conjunction with the Navy at Pax River and these are the ratings so you can understand the viewgraphs coming up: 1 - Poor, 2 - Fair, 3 - Good, 4 - Excellent, and 5 - Outstanding. It was done in November 1984. I wanted to show you the actual survey and I didn't want to bias anyone so I put all of it up there.

The first question was: 1. "How would you rate the HUD as the primary attitude reference including primary source for attitude, airspeed, altitude, vertical speed, AOA, Mach and G, for the following tasks:

a. Quick interpretation for unusual attitude recovery: the mean - 3.2; generally good. You see a lot of excellents and outstandings in there.

b. For expeditiously determining aircraft parameters: mean - 3.7; almost an excellent.

c. Recovery from vertigo: mean - 3.8; almost an excellent

d. And we looked at some of the basic instrument tasks. And one of them was leveling off at desired altitude expeditiously: mean - 4.2; beyond excellent.

2. Rate the usefulness of the ADI selector on the VDI: mean - 2.6; fair; they don't use it.

Now you have all seen a picture of the F-15E Dual Role Fighter (DRF) (Figure 11) which has adopted basically the same philosophy we forwarded on the F-18 and the whole concept of MFD offering or affording flexibility is an issue. I think there is a point of diminishing returns for flexibility. I think the F-18 and the F-15E are attempting to tackle that problem by allowing the pilot to program what he wants to be available. And that can be done either by a data transfer module or some method within the crew station. So flexibility does not have to be an inhibitor. It can be used intelligently.

What does the future hold? Well, what I really think it holds is the integration of attitude information into all tactical headup/headdown displays in a manner that is non-intrusive. Now, one of the ways we are looking at doing that is this: that up front control area is prime real estate in the crew station (Figure 12). Boy I'll tell you, it is just right there. With the advent of new technologies such as flat panel liquid crystal/LED devices, we are looking seriously at using that real estate as MFD that can display attitude if you want it, and it can also give you your up front control

F-15E Forward Cockpit

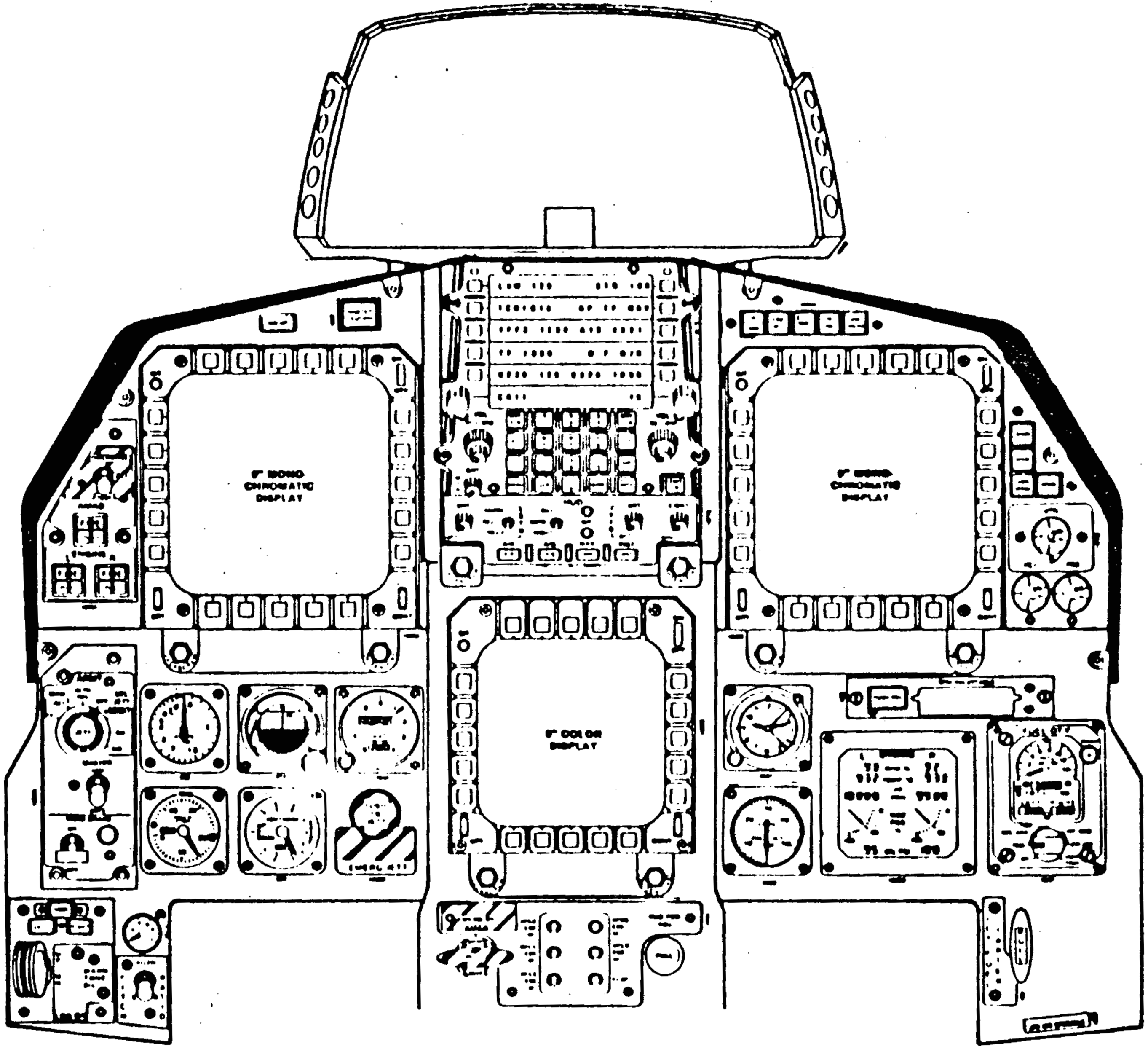

Figure 11

9

UP-FRONT CONTROL/DISPLAY

TOUCH SENSITIVE/FLAT PANEL

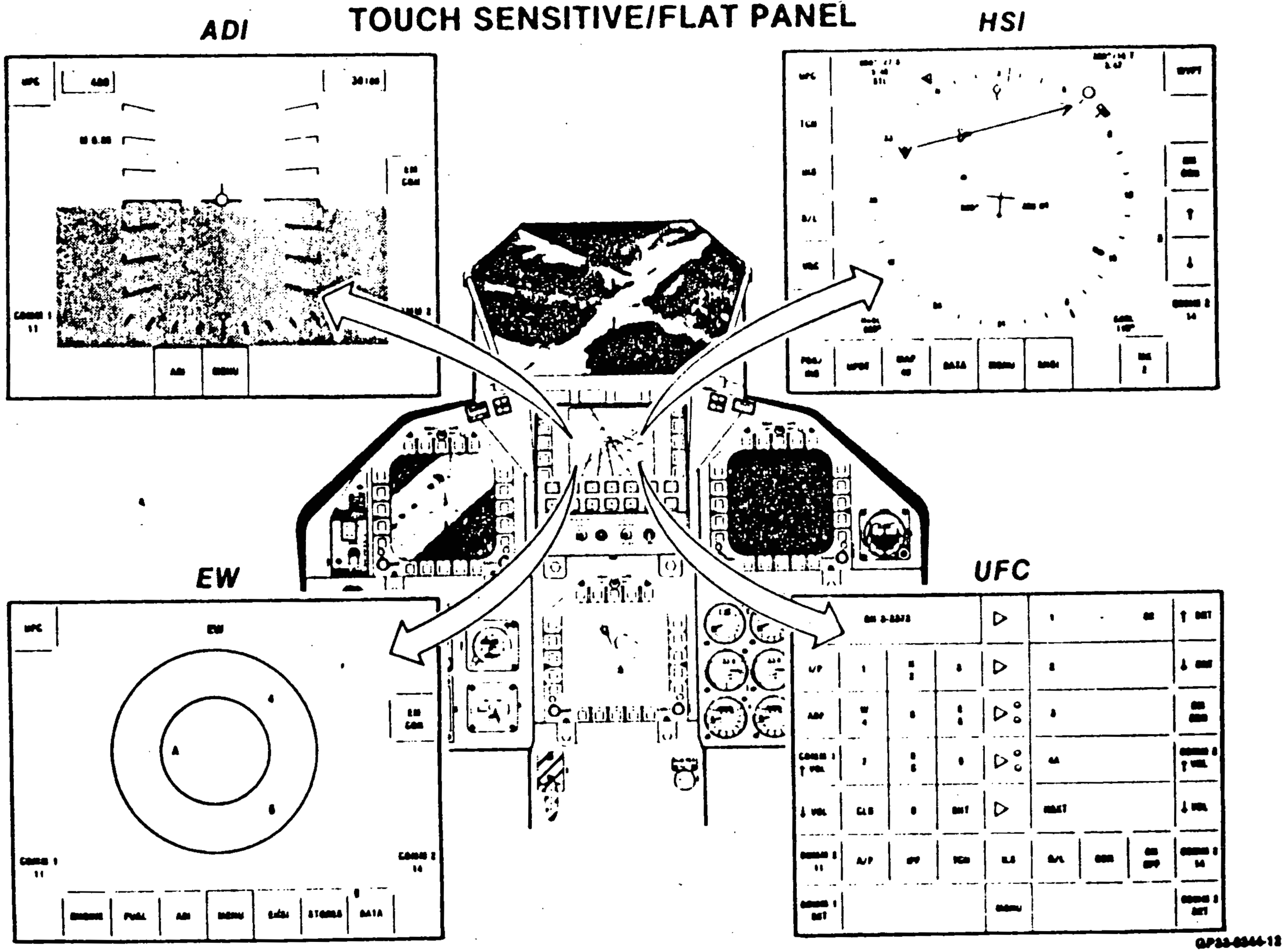

Figure 12

Future Head-Down Displays

(Intercept)

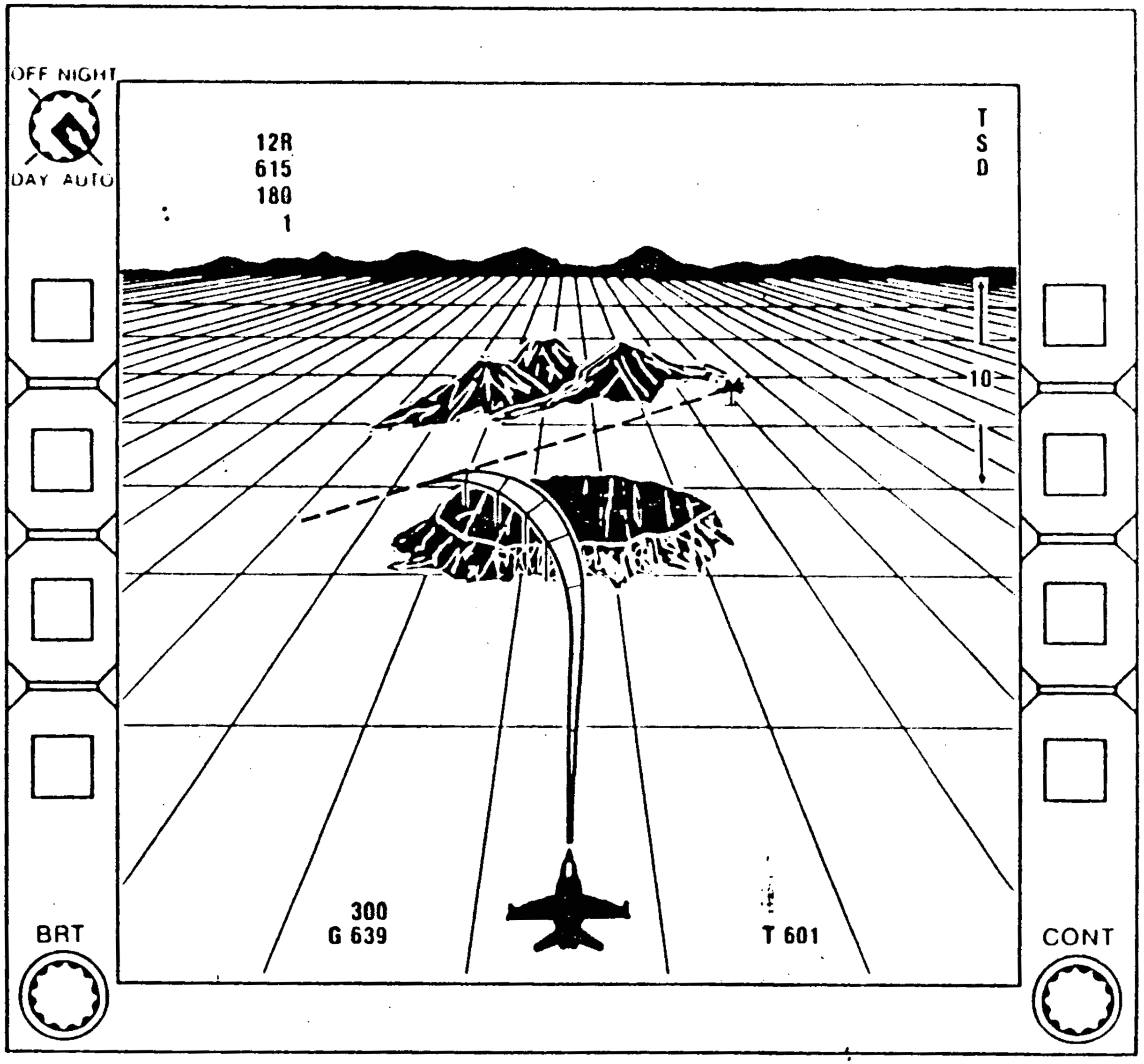

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Figure 13

functions: electronic warfare, your navigation, intercept geometry (Fig 13), whatever you desire can be put there. And we are actually flying one now in the F-18. (Fig 14) So if you want that big ADI right in front of your eyes, you can have it. But, let's not limit the flexibility, let's not dedicate the instrumentation.

With the advent of color graphics, it makes it very simple for us, by utilization of perspective display formats, to give attitude information on all crew station displays very easily and highly interpretively. We are also looking at concepts for new HUD formats or head up formats in toto. Now I believe Col Ercoline mentioned the fixed horizon reference and the moving aircraft (Crane Alweather Flite Gage). I think that will work fine for head down, but as soon as you put some thing head up, the horizon and the earth reference have to match the horizon and earth reference being depicted outside or else your gyros topple. So in that vein, I think it is essential that we keep all the displays extremely similar in their orientation. (Editor's note: Those of us who have flown the Crane Gage, which is an outside-in display similar to presentations in video-arcades, find it to be very easy. Even head-up, it does not tumble your gyros. And the reason is simple: the roll-sensing is direct, not reversed, as it is on inside-out displays like HUD's and ADI's. When you look at an ADI or HUD, you must mentally transpose back to outside-in, which takes time and occasionally leads to roll-reversals. The Crane Gage does this step for you. i.e. it organizes your attitude information in a way that requires no interpretation. It's intuitive, faster and not subject to the confusion of inside-out displays.)

These are some examples of what we are doing to look at some advance HUD formats that totally eliminate the need for pitch ladders (Figure 15), where you can display an earth reference and show aircraft aspect; and really, that is all the information you need for combat. Now for instrument approaches where you need to establish a 1 1/2 or 3 degree glide slope, that's another issue; and that can be brought up.

An example of a potential unusual attitude situation: that is fairly interpretable; you have to roll left and pull, and if you want we can even put an arrow to tell you which way to put the stick. It is not that hard to do.

With the advent or the recent advances in CRT technology and helmet materials we are very big proponents of helmet mounted sights and displays (Figure 16). We think they have a very, very large future. If we can give you a display that will weigh less than 2 pounds, less than the current HGU-55, give you accuracy within 5 milliradians or so, and FOV essentially as wide as you want, we can show you all aspects of attitude information continuously. So when you are looking back here checking 6 or checking the bogeys, you don't have to constantly scan the HUD to find out what your attitude information is. It is always displayed to you in one little corner of your visor. You simply move your eyeball. And a typical representation

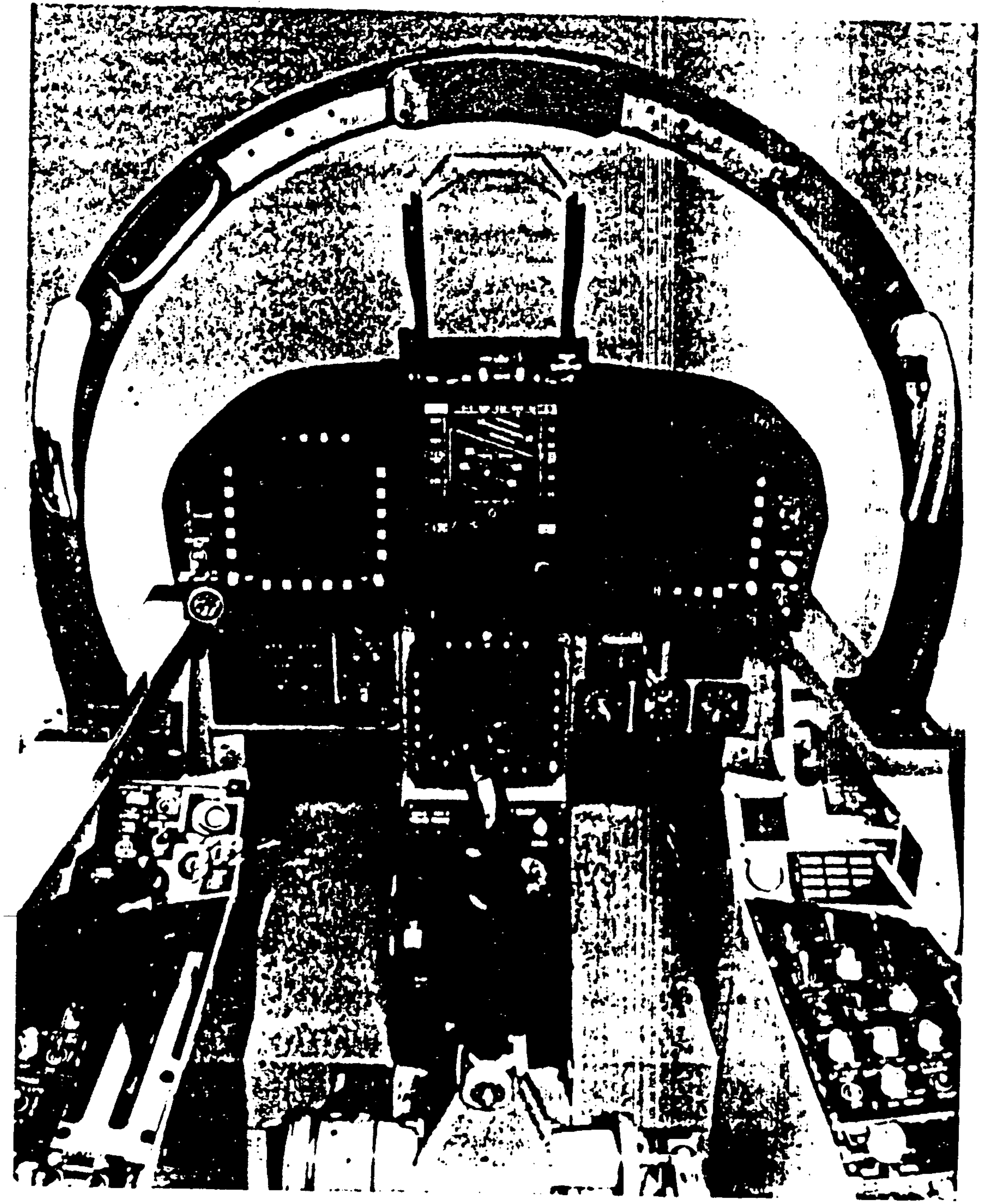
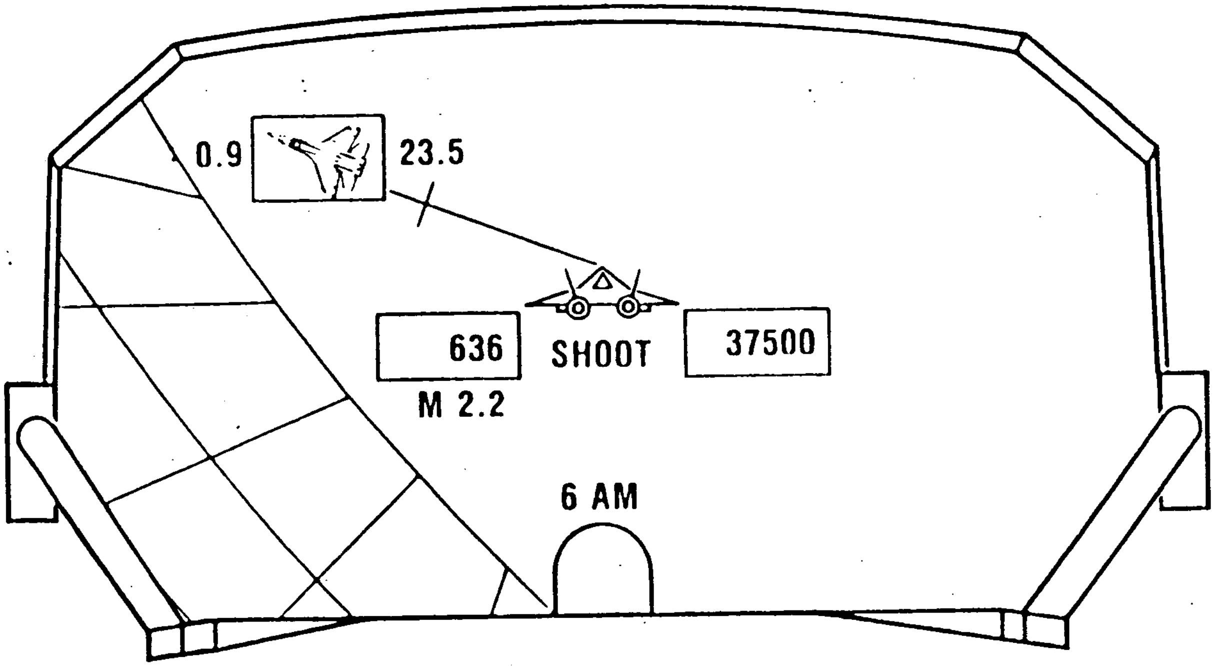


Figure 14

Future HUD Formats



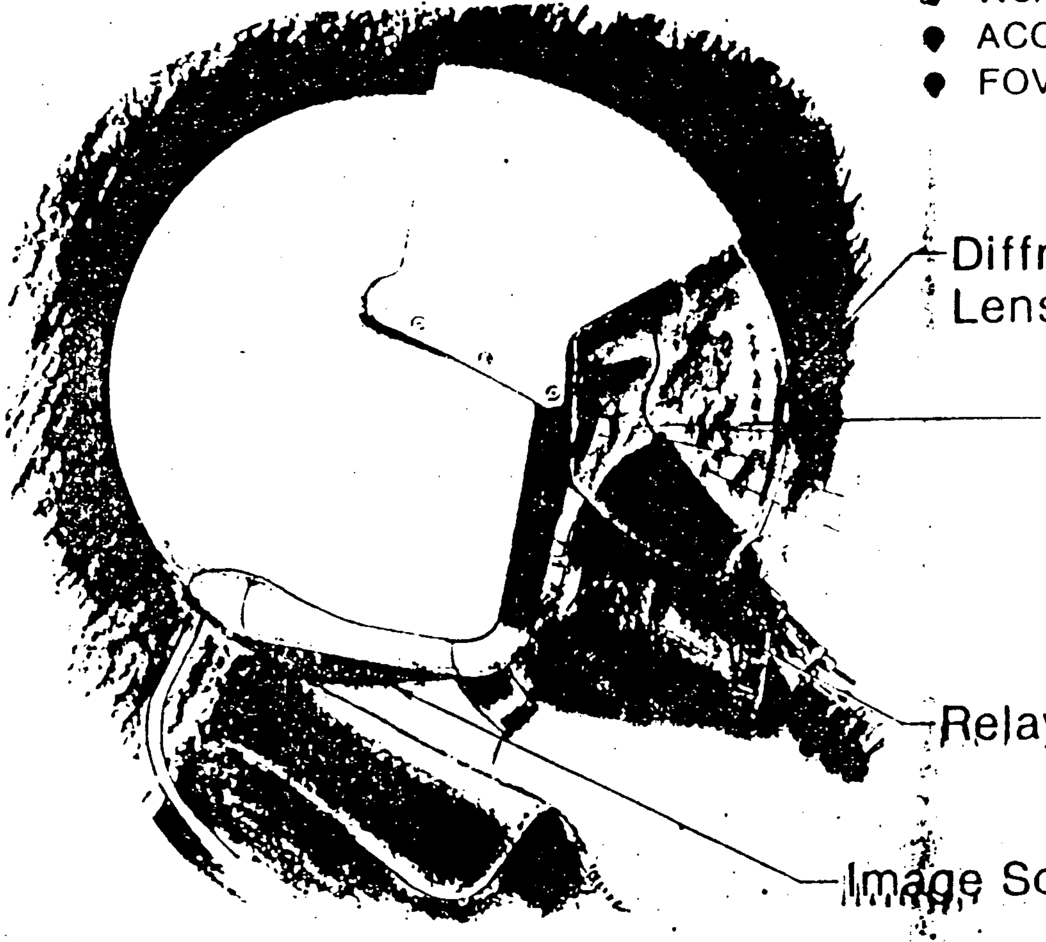
- Will Use Color to Highlight Important Information
- Will Use Pictorial Representations to Illustrate Critical Attitude and Weapon System Features

GP51 0044 5

Figure 15

Helmet-Mounted Sight/Display

- Weight .... < 2 lb
- ACC .... 1/2 deg
- FOV .... 10 deg/min



Diffraction Lens

Relay Optics

Image Source (CRT)

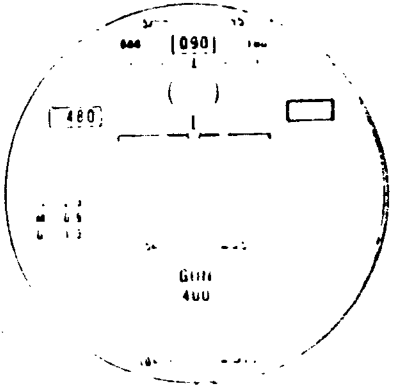


Figure 16

might look something like that. It's just an artist's rendition. But where ever you look you have attitude information.

In conclusion, (Figure 17) I guess you can tell I'm an advocate of MFDs. There are some other issues that I think should be addressed. Future airplanes, as an example, if the Air Force makes a decision later to supine a pilot, on an articulating seat as an example, to enhance G tolerance, what does that do to your instrument panel? It compresses it vertically. It may not affect the horizontal dimension, but certainly the vertical dimension is compressed. Well now, if you put a round dedicated ADI ball you have destroyed 30% of your instrument panel. I think we need to allow the attitude awareness information to be combined with other tactical formats and we can do it intelligently now, you know.

The F-15 had its first flight in 1972, approximately. The ATF will first fly in 1992 . That's 20 years. We have learned something. What I'm asking is that you let us apply that learning to something that we think will work. Color, as mentioned before, is an extremely useful tool for highlighting and decluttering . MFDs allow us to accommodate pilot preference. Now you know pilots are like snowflakes. There are no two alike other than they are all jocks. I worked on F-15 aircrew systems, F-18 aircrew systems advisory panels, and they would rotate through every year, year and a half or so, and everybody wanted something else. Put an ADI ball here, no put it here, put it here. No one is ever happy. Well we'll let you put it where you want. Let you program the airplane the way you prefer to have it. And it does offer us, the designers, programming flexibility. What I mean by that is that it allows us to accommodate changes in weapon systems, future changes in design parameters, that come along after the aircraft is built without expensive retrofitting. We can take an LST pod or a FLIR pod or a laser pod and throw it on the F-18 and display whatever that information has to offer. So if affords us and it affords you that added blast for your dollar.

What I'd like to do now before we take any questions if there are any, is to introduce Maj Laurie Hawn from the Canadian Air Force. There was a recent incident involving an F-18, if you will, a Canadian F-18, that I thought would be interesting to see the video tape.

CANADIAN FORCES EXPERIMENT WITH THE CF18

Major Laurie Hawn, CFB Cold Lake, Alberta, Canada

At the risk of talking out of the wrong interchange of the parts, I would just like to give you a real quick Canadian perspective on what we are doing with HUD's flying with the F-18. We have never had an aircraft with a HUD before. We have about 20,000 hours with the airplane overall right now. I

Conclusions

Multifunction Displays

- Yield Maximum Flexibility for Main Instrument Panel
- Allow Attitude Awareness Information to Be Combined With Other Tactical Formats
- Allow the Use of Color Highlighting
- Accommodate Pilot Preference
- Offer Programming Flexibility

GPS1 0044 531

Figure 17

have about 500 myself. We were a little concerned about the HUD and about how we were going to adapt to it. Just to go along with some of the things Paul was saying, we found the transition to that digital type HUD with the lack of trends to be disconcerting for the first 2 or 3 or four trips but after that, pretty well everybody, including the pipe-line guy who comes out of our training mill at Moosejaw with the T-bird and round dials and such figures it out pretty quickly and adapts to it pretty quickly. The head up obviously is our only option. We don't have a head down option other than to put the head up display on one of our head down displays. So far that has not caused us a problem.

We have had a couple of incidents and we're gonna have more, I'm sure, that are going to be fairly similar to this incident (runs VTR of mishap F-18, Cold Lake). What happens is the target is at 1200 feet and the cloud layer is at 10,000 feet. The guy fires a Sparrow at the front and goes around for a re-attack with the sidewinder at the stern. What he does and what he gets is not so much a loss of attitude awareness as it is, what I heard yesterday, is overloaded: getting preoccupied with the radar and just forgetting to fly the airplane. And what you'll see as he goes into the reattack, he breaks to the left and goes back around to the right and instead of putting the target on the nose, he thinks he has the target on the nose, he's not looking at the HUD, he is looking at the radar; in fact, he has the nose buried and he is in fact going down instead of up and you'll see the target designator box up in the top left hand corner sitting there flashing saying, "Hey dummy, the target's up here, but its HUD limited; it's up in that direction. He is also accelerating. He misinterprets the target airspeed; he thinks the target is supersonic, but it's not, so he rolls fairly rapidly into a 135 degrees of right bank, puts about 4 or 5 g on the airplane, and is accelerating from 500 to 700 knots, so you can imagine what is happening to his internal gyro. Okay he has just taken the Fox 1. There's the target designator box; left, back around to the right to the sidewinder shot. That's where he thinks the target is supersonic. There's the target up there. He in fact thinks the target is down instead of up.

Where it gets black here is where he starts to come out of a cloud about 2000 feet or a little less above ground. If you watch it down you can see. He comes out of the cloud about 35 degrees getting close to 700 knots. You can't hear it now , but there is a sharp intake of breath, then there is silence because he is holding his breath and basically he just buries the pole. If you watch the g build up (somebody mentioned Miller's work, 4 g in 2 seconds) this is about 11 g in one second. The altitude goes down to 2200 feet; elevation in that area was about 2050 feet. Though the HUD showed 11.1 g's, the tapes in the airplane, showed in fact it was 11.4. An advertisement for Navy airplanes--they took it apart and there was nothing wrong, no rivets popped anywhere. They put it back on the line: however, everyone keeps that tail number in the back of their mind.

Ten minutes after that incident we lost our first CF-18 in similar type circumstances at the same base. The target was at low altitude down at 500 feet. The guy did a similar type of thing. He fired a Sparrow in front, went to reattack, stayed too high too long, wound up in a slicing type maneuver, probably had a break lock in the beam, got too preoccupied with the radar, and when he came out of the cloud at 1700 feet, it was calculated that if he had pulled the handles right then he would have made it. But, that is not your first reaction. Your first reaction is to say, "Oh shit." As soon as he did that it was all over. He went in with the airplane. The point of it I guess is not so much attitude; the attitude awareness ability of it is there on that HUD with the angle of pitch ladder and so on. The point was made yesterday that in airplanes like this with so much information available, it is really not, in this case, attitude awareness as it is pilot overload or preoccupation with the task at hand. The point of interest on this is that in both these incidents, the guys did not haveattitude information displayed--you can declutter the displays to where you don't have that attitude information on the radar display. In both these incidents the display was decluttered and that attitude information was not there. Our standard sort of position is that when it is day VFR you're off, you don't need it, but when its night, IMC you for sure need that attitude information. At that time, we didn't have a simulator that was capable of providing night or in-weather IMC intercept training, especially low altitude. We do now. The point was made yesterday, we really have to get to the grownups, it's going to cost money for simulators but in the end that's cheaper than smoking holes. One of our initiatives is that we use the F-5 as a lead-in to the F-18. And right now we're trying to update the avionics in the F-5 to include an F-18 style HUD, with the same type of digital displays, to make that training transferable from the F-5 to the F-18. We like the HUD. Guys do generally fly with the HUD symbology called up on one of the MFD's, but it's only because there are two symbol different symbol generators, and if you lose one of the symbol generators, you'll still have the HUD attitude displayed there right now and won't have to call it up. So though we do fly with it down there, we fly with the HUD all the time, IFR approaches and everything. It disappears if you enter a spin - then automatic spin recovery information pops up and attitude information goes away. HUD information also disappears or is much harder to see if you are flying into the sun: another reason to repeat it head-down.

LTC William Ercoline: You say you had attitude information on the radar scope in the two F-18 incidents you described?

Laurie Hawn: No, they did not have it called up. However, you have the option for horizon line and velocity vectors. In these two instances, it was decluttered and not up there. When displayed, if the velocity vector gets HUD limited (reaches a limit), it will sit there and flash at you - which may get your attention. The other thing we've asked Mac Air for, as a result of these two accidents, is a baro-altitude voice warning. The radar altimeter is great except in unusual attitudes where it can't see the surface, so we want a baro-altitude voice warning as well, that we could preset at some predetermined altitude.

Col Gary Matthes: I've got a comment and a question: MFD's are great things but tailoring the cockpit individually may be a problem. We found early in the F-16 program, that the more flexibility you give the more complexity you get, and if the guy doesn't get it sorted out on the ground, there's total confusion in the cockpit. And if that happens to be at night, he could be dead. So you need to make sure you don't provide so much flexibility that the guy who grew up on T-38's looks at all those possibilities the first time and doesn't have a clue how to handle it. If he handles it wrong, if he calls up the wrong display at the wrong time, it could be hazardous. Let me ask a question, though: in your survey with the USN, one question I didn't see there and which would seem important: had any of those pilots who rated the HUD for unusual attitude recoveries ever actually been there using that HUD other than in VMC?

Summers: They were all test pilots.

Col. Gary Matthes: But, what I'm asking is different: he could have 5000 hours of flying but if he's never done the maneuver of unusual attitude recoveries using that HUD, then he's probably not really qualified to answer that question.

Laurie Hawn: We, as a matter of training, do that in the simulator with the pilot but the way we teach unusual attitudes in the airplane as well is when the guy first goes to the HUD, if he can't figure it out right now, with the angled pitch ladders (and it really is kinda easy: if you'll just put that arrow straight up at the top of your helmet and pull, you're gonna find the horizon) But, if he looks at it and he can't find it right away, we tell him to go down, shitty as it is, to that standby ADI just to get the white-black. Am I going up or am I going down. And as soon as he gets that established, then back to the HUD. But guys generally don't have to do that. Very, very seldom do they have to do that.

Matthes: VMC or IMC?

Laurie Hawn: Well, in the simulator, IMC, which is as close as we can get.

I did a survey of vertigo among pilots flying HUD-equipped aircraft including the F-15 and two years ago we updated it to include the F-18, and F-18 pilots seemed to have less SDO than pilots of previous aircraft.

Summers: I wonder if there's a learning curve associated with that. We also included some French pilots who also had a lower incidence of SDO - so my conclusion is you've either done a better job of integrating head-up with head-down displays. Obviously, the F-18 has a well<u>integrated</u> cockpit and a superior HUD. You've probably done a better job of training and a better job of integrating.

LTC Lorenzo Pugh: One of the things you said that disturbs me is that if the guy needs the ADI, he can always call it up. What I'm submitting is, if you need an ADI for SDO vertigo or whatever the situatio is, you don't have time to call it up.

Summers: Well, that's an interesting question and let me address it first before mentioning the automatic spin mode in the airplane. We found early in the test program that the aircraft had a mode of getting into a flat spin. That was a surprise to us and we lost an airplane. We took some steps that when the F-18 detected itself to be in a spin, it put up an automatic spin recovery display telling the pilot exactly where to put the stick and when to do it, and we've had no problem with it. The airplanes now are smart and they're getting smarter. There are a lot of things we can do automatically as well as manually, to afford rapid pitch reference inside the crew-station, and it could be code tapping in on throttle and stick, it could be automatic based on aircraft sensing like we do for the spin mode; there are a lot of things that could be done, and we haven't really investigated that fully, and I think we need to. But, I would hate to destroy the HUD or Head-up concept including helmet mounted sights, because of some early bad experiences. We're learning. The HUD's been around, what, 20 years? The ADI's been around, what, 50-60 years? Give us an equal chance.

LTC Lorenzo Pugh: But, what if you are wrong? You know, the operational units are the real test bed. You're using test pilots in VFR conditions to check the systems out but the operational pilots go to combat at might in the weather and in IMC, and if they find out then you're wrong, like the F-16 with the small ADI and bad instruments, then guys die because your theory was wrong and you didn't use enough of the right data to test and insure it would work before installing it in the aircraft. What are you doing about it?

Summers: Oh, I think all aircrew advisory panels or equivalents are needed as an integral portion of our design team, and they need to be a mix of experienced and nuggets to help alleviate that situation. And we've tried to do that to a great extent, not always successfully because both the AF and USN try to send their best jocks in, but I think we need to force that issue and make it a mix. I felt before any critical design decision was made that we'd wrung it out fairly well, but I think that process needs to be continued and emphasized.

Unrecognized: What's the difference in reliability between MFD's and the old electro-mechanical displays?

Summers: I looked at the data just before coming because I was sure that question would arise. The current F-15 ADI ball has a 630 hour MTBF. I don't know if that's occurring or if that's specification value. The F-15E, I believe, I'm not sure if it's F-15E or F-18 MFD has an 830 hour MTBF. Now with the advent of flat panel displays, we're talking in terms of probably close to 5000-8000 hours MTBF in the next generation of aircraft. With dual redundant processors, display options if you will, that are capable of driving the display on battery power as well as generator power, it almost becomes a moot point. It winds up in the white noise. I'm not sure that's as much of an issue as it was in the past, but as contractors, we still need to investigate it.

Col McNaughton: I'd like to reiterate my comment that there are instances when a pilot may not know he needs an ADI, and that's when he really needs one. I feel strongly that he needs something up there dedicated full time. An example is during the Pop-up/Pull-down ordnance delivery pass. You pop-up upright, roll inverted for the pull-down, then roll out upright looking for the target. It is possible to become so engrossed in getting that pipper on the target that you forget you've rolled out. The display on the HUD does not tell you instantly whether you're upright or inverted. Believing yourself to still be inverted, you roll 180o and pull-right into the ground. That may sound ridiculous buy it happened to me on at least 2 of perhaps 20 or 30 such passes in the LANTIRN simulator. The simulator project officer, MAJ Tony Orr admitted that other real fighter pilots had made the same mistake.

So, I reiterate my point: you need an attitude display full-time to provide instantly the Big Picture: whether you're upright/inverted, climbing/diving or if so to about what degree just to prevent those kinds of errors.

FREQUENCY-SEPARATION: A THIRD ALTERNATIVE IN THE OUTSIDE-IN/INSIDE-OUT CONTROVERSY

Stanley N. Roscoe, New Mexico State University
and Illiana Aviations Sciences

BIOGRAPHY

Stanley N. Roscoe is a Professor of Psychology at New Mexico State University and Head of the Behavioral Engineering Laboratory. He is also Professor Emeritus of the University of Illinois and President of Illiana Aviation Sciences Limited. He received his Ph.D. in psychology from the University of Illinois in 1950, and for many years was affiliated with both the University of Illinois and Hughes Aircraft Company. Dr. Roscoe's research interests include visual accommodation and spatial orientation; computer-animated display and control systems; automated pilot selection testing; flight simulation and automated airmanship training; and aviation accident investigation, analysis, and simulation.

From 1943 to 1946, he served in the U.S. Army Air Corps as a flight instructor and as a transport pilot in the Pacific Theatre. From 1946 to 1952 he progressed from Research Assistant to Assistant Professor at the Aviation Psychology Laboratory, University of Illinois at Urbana-Champaign, where he conducted research on flight display principles and pilot performance. In 1952 he joined Hughes Aircraft Company where he established a human factors research and engineering program and advanced to Manager of the Display Systems Department.

He returned to Illinois in 1969 to establish the Aviation Research Laboratory with a staff of approximately 50, including an annual average of about 25 graduate research assistants. From 1969 through 1974, as the Associate Director for Research of the University's Institute of Aviation, he developed and directed an interdisciplinary program of analysis, design, and experimentation at ARL. More than 70 advanced degrees in the behavioral, engineering, and computing sciences were earned by graduate students engaged in research programs for which he was the Principal Investigator.

In 1975-77, once again with Hughes Aircraft while on leave from Illinois, he investigated visual perception with imaging displays at NASA's Ames Research Center. In 1977, he retired from Hughes and returned to Illinois to continue his investigation of judgments of apparent size and distance, eye accommodation, and associated visual illusions in flight. Concurrently, he formed Illiana Aviation Sciences, an extracurricular contract research and consulting group. In 1979, he retired from the University of Illinois to join New Mexico State University and establish the Behavioral Engineering Laboratory.

He has more than 200 publications, including the book Aviation Psychology, 1980. He has been a Technical Advisor to RTCA, FAA, NASA, and the US Army, Navy, and Air Force and has served as a consultant to the Royal Swedish Air Force, Air Line Pilots Association, Allied Pilots Association, United Air Lines, National Highway Traffic Safety Administration, National Academy of Sciences, and various law firms involved in aviation accident litigation. He has held several offices and received numerous awards from the Human Factors Aeronautical Society of Great Britian.

In the late evening of the first day of 1978, an Air India 747 took off from Santa Cruz Airport in Bombay, bound for Dubai, United Arab Emirates. As the airplane climbed out over the Arabian Sea and the surface lights passed out of view, Captain Kukar gently rolled into a 14° bank to the right with aileron inputs varying from 9 to 16° during the interval 62 to 70 seconds after liftoff. Captain Kukar relaxed his aileron pressure over the next 13 seconds, and the plane gradually returned to wings-level. Then it continued to roll, slowly, into a 9° left bank.

At this point Captain Kukar made an abrupt left-aileron input, momentarily reversed his input, then went back to hard-over left. From an altitude of 1,460 feet the big Boeing rolled into a 108° left bank, 35 degrees nose down, and crashed into the sea at an airspeed of 330 knots just 101 seconds after liftoff, killing all 210 aboard. Captain Kukar held hard-left aileron and rudder to the end.

The cockpit voice recorder preserved the following barely intelligible words:

> At 87 seconds after liftoff, with a 32° left bank and rolling left, Captain Kukar exclaimed, "Arey yar, my instrument!"
>
> Two seconds later, with the bank now at 47°, First Officer Virmani replied, "My...mine's also (toppled?) [not clearly intelligible]," and Captain Kukar simultaneously said, "Check your instrument."
>
> At 95 seconds, First Officer Virmani repeated [more clearly], "Mine has also toppled."
>
> One second later, just 5 seconds before impact, Flight Engineer Fario interjected, "No but, go by this, Captain."
>
> At 99, Captain Kukar: "Just check the instrument. Yar!"
>
> At 101, First Officer Virmani: "Check what?" (Sound of impact.)

For whatever reason, Captain Kukar evidently was confused by the attitude indication of his flight director instrument, and Flight Engineer Fario diagnosed the cause of the Captain's confusion and tried to redirect his attention to another instrument, possibly the turn indicator.

PROBLEM

Making such bank-control reversals while using a conventional attitude indicator is primarily a general aviation problem. But even airline pilots, military pilots, and professional test pilots occasionally perceive the moving horizon line on such instruments as if it represented the wings of the airplane instead of a fixed reference against which the plane is moving. For example, an F-86D scope-camera movie of an air-to-air attack by, of all people, Chuck McDaniel, our chief test pilot at Hughes Aircraft, clearly recorded such a horizon-control reversal. Fortunately, it happened at a high altitude on a clear day. But McDaniel will never forget an experience he could not explain until he also saw the scope movie. And that, he could scarcely believe.

Years of research have shown that in the absence of specific training to the contrary, a human's "natural," or stereotypic, response under a wide variety of experimental conditions is to expect a display element to move in the same direction as the control input. (Evidently because we make the control input we identify ourselves with the element that moves.) So when a sudden input results in display motion in the direction opposite to that expected, the identity of the moving display element may become momentarily amibiguous or actually reversed. That is why I believe that to assure correct roll and pitch responses in all circumstances, it is necessary that the airplane symbol be seen as the moving "figure" against the fixed "background" of the external world.

A pilot's perception of banked and wings-level flight comes through two sensory organs, the eye and the inner ear. When one set of sensations contradicts the other, the pilot must choose which to trust, and vertigo may result. The real problem in flight arises when an aircraft accelerates about its roll axis below the pilot's vestibular (inner ear) sensory threshold. If the pilot's attention is diverted during this time, when he shifts his attention back to the attitude indicator, he will find the display portraying an unexpected attitude. That will result in a conflict between his vestibular sensations, which tell him he is flying straight and level, and his visual sensations, which tell him he is in a banked attitude.

Should he initiate a sharp control movement to correct the undesired attitude shown on the display, he will feel as though he is rotating from a wings-level attitude into a bank, when just the opposite is the case. In other words, his eyes will tell him positively that his is correcting an undesirable situation, while his vestibular sensations will tell him positively that his is moving into one. In this situation, the vestibular sensations can be so compelling that the pilot will reverse his visual attitude reference for the brief remainder of his life. This is my theory of what happened in Bombay.

POTENTIAL SOLUTION

During the past 40 years, the problems and potential solutions associated with flight attitude awareness have received much experimental study in flight simulators and some, but much less, in flight. The most comprehensive and objective flight experiments were conducted at the University of Illinois during the early 1970s and reported in detail in the August 1975 issue of Human Factors (Beringer, Williges, and Roscoe, 1975; Ince, Williges, and Roscoe, 1975, Roscoe and Williges, 1975). They are summarized in Chapter 7 of my book, Aviation Psychology (Roscoe, 1980), which is included as an appendix to this paper.

In my younger days, I waged a futile battle for a switch to an "outside-in" moving airplane attitude presentation. (The North American F-108 mockup board did vote unanimously to do so one week before the airplane was cancelled in favor of the Lockheed YF-12.) But the bank-reversal problem with the "inside-out" moving horizon remains, and a different solution is required. A good one, experimentally validated in the University of Illinois experiments sponsored by the Office of Naval Research, is to have both symbols--airplane and horizon--move.

Such a dual-movement display is known as a "frequency-separated" presentation. Although it sounds confusing, it's extremely clear in use. Changes in aircraft attitude, which are relatively slow (low-frequency responses), are displayed as they always have been by a moving horizon indication. The airplane symbol rotates in direct response to--and in the same direction as--the relatively fast aileron control inputs (high-frequency responses). Thus, the rapid initial display motion is directionally compatible with the plane's actual motion and predictive of its imminent attitude.

The results of the Illinois study of the flight transition of professional pilots to the frequency-separated attitude display in a variety of operationally realistic flight tasks, together with the results of experiments involving subjects with little flight experience, place the display in a unique position. Nonpilots and pilots of little experience readily learn to use it and show little tendency toward control reversals to which inexperienced pilots are subject with the conventional moving horizon. Highly experienced pilots readily adapt to it as a moving horizon display to which only a roll-rate prediction has been added, to assist them in maneuvering the airplane.

I believe that the frequency of design-induced bank-reversal errors with the conventional moving horizon is much higher than is generally recognized. In addition to losses in lives and equipment, the consequences of sticking with moving horizon displays include the need for more pilot training than would otherwise be required. And who knows, in this age of fierce product liability litigation, we may be only a step away from a court decision in which a manufacturer will be found responsible for design-induced pilot errors because ways of guarding against them are scientifically established and yet the manufacturer chose not to implement a change in display.

CURRENT ISSUES AND APPLICATIONS

The problem of spatial misorientation has been exacerbated by the use of collimated virtual imaging flight displays. For many pilots these head-up or helmet-mounted displays prevent the eyes from focusing at the real (or simulated) distances of outside objects (Hull, Gill, and Roscoe, 1982; Iavecchia, 1985; Norman and Ehrlich, 1985; Randle, Roscoe, and Petitt, 1980). Evidently collimation releases the eyes to lapse toward their dark focus (which varies widely from person to person), and the bold symbology of typical head-up displays does not require sharp focusing for legibility. In any case, collimation does not cause the eyes to focus at optical infinity as the advocates of HUDs and HMDs assert, and the consequences are the inability of most pilots to attend concurrently to the collimated symbology and distant objects without conscious focus shifting and associated losses in distant acuity and veridical spatial orientation.

In the context of spatial orientation, misaccommodation can have several adverse consequences. Depending on the direction of the difference between focal distance and object distance, objects will appear smaller or larger than lifesize and more or less distant. If the eyes focus too near, as they do when viewing distant scenes through collimated symbolic imagery, objects such as airport runways or surface targets appear shrunken and more distant than they are and consequently higher in the visual field relative to the horizon. As a result, pilots tend to come in too fast, round out high, and land long and hard. They also overestimate the distance to ground targets and pull up too late.

Furthermore, misaccommodation not only blurs images, but the blurring serves to reduce contrast, further interfering with object recognition. Because few pilots can attend to outside objects and collimated symbology simultaneously, conscious switching of attention is necessary. If a pilot dwells too long on either the collimated symbology or outside objects not offering a strong horizontal reference, the pilot may be unaware of gradual attitude changes. In such a case, a suddenly noticed angled orientation of the symbolic horizon bar or pitch ladder can result in a perceptually overpowering attitude reversal and a screaming spiral dive in to the dirt. To provide a HUD as the sole attitude display in the C-17, as currently planned, will cost lives and airplanes.

APPENDIX

"Display Motion Relationships" by Stanley N. Roscoe, Steven L. Johnson, and Robert C. Williges: Chapter Seven from S.N. Roscoe (1980). Aviation Psychology (pp. 68-81). Ames, IA: Iowa State University Press.

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7

DISPLAY MOTION RELATIONSHIPS

Stanley N. Roscoe, Steven L. Johnson, Robert C. Williges

DYNAMIC displays convey information by the positions of their moving parts. The display designer must decide on one of the many possible coordinate systems within which elements of the display are to move. This decision, often quite arbitrary, determines whether the elements that move represent the pilot's airplane or the outside world. The consequences of this choice are not trivial. In the United States during any year about 100 people die because pilots become disoriented relative to the outside world and fly into the ground in a high-speed spiral dive. Entry into a spiral dive follows entry into a cloud, a shift in visual reference from the outside world to the flight instruments, and a reversed response to the "artificial horizon" (Johnson and Roscoe 1972).

DEFINITION OF TERMS

The two basic coordinate systems in which spatial flight information may be displayed are earth coordinates and aircraft coordinates. *Earth coordinates* refer to three orthogonal axes fixed in position relative to terrestrial space, as opposed to inertial or celestial space. One axis is vertical and emanates from the center of the earth; the second is orthogonal to the first and is aligned with the north pole; the third is orthogonal to the first and second. *Aircraft coordinates* refer to the longitudinal, lateral, and vertical (x, y, and z) axes of the aircraft.

When flight attitude is presented in aircraft coordinates, the artificial (gyro-driven) horizon bar rolls and pitches relative to the coordinates of the aircraft's panel-mounted display. This conventional presentation is commonly referred to as "inside-out," "moving horizon," or "moving outside world." Alternatively, a "moving airplane" symbol representing the pilot's own craft as viewed from the rear, or "outside-in," rolls and pitches in the reversed directions relative to display coordinates. These basic alternative sets of coordinates are not limited to the presentation of

flight attitude but apply to any spatial information, including geographic position and altitude and their derivatives.

WHAT SHOULD MOVE?

In attempting to determine the preferred motion relationships among display symbols and their real-world counterparts, it is necessary to consider the question of whether the pilot thinks that the display represents the vehicle moving against the external world or the external world moving about the vehicle. This question involves what has been termed the pilot's "frame of reference." With respect to the presentation of aircraft attitude, the issue is illustrated graphically in Exhibit 7.1. In whatever manner attitude information is displayed, it is necessary for the pilot to think that the aircraft is moving. If the outside world appears to move, the pilot is disoriented and subject to vertigo.

From the date of invention of gyroscopic flight instruments, including turn indicators, directional gyros, and attitude gyros, the frame of reference for display presentation has been a subject of controversy. The argument found its way into the literature early and was stimulated greatly by the fog flying exploits of James Doolittle under the sponsorship of the Daniel Guggenheim Fund (1929; 1930). On September 24, 1929, Doolittle proved conclusively that it was possible to take off and land an airplane by instruments alone.

Doolittle took off with the cockpit of the airplane completely covered, flew a distance of 20 miles, and landed at almost exactly the same spot from which he had taken off. The attitude indicator used by Doolittle was

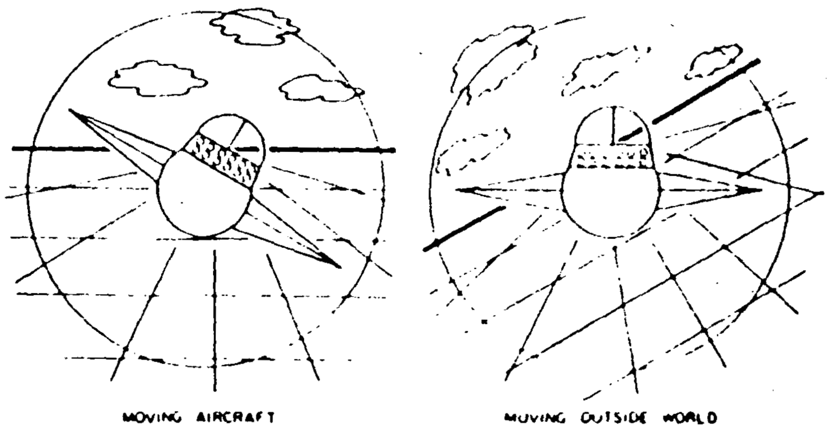

EXHIBIT 7.1. Illustration of the basic figure-ground controversy in the presentation of aircraft attitude *(Johnson and Roscoe 1972)*.

the Sperry Horizon, which was the prototype for the conventional artificial horizon presentation used today. Poppen (1936), a naval flight surgeon, presented a rationale for the motion relationship of the Sperry Horizon used by Doolittle, namely, that the correct form of presentation was an exact analog of what would be viewed through the windscreen in contact flight.

Essentially, Poppen considered the display to be a porthole through which the pilot views a symbolic analog of the real horizon. Poppen carried this line of reasoning to the point of advocating a displacement of the gyroscopic turn needle to the left while in a right turn so as to keep the display index in proper perspective (perpendicular) to the external world. This same rationale has prevailed through the years in support of the moving horizon attitude presentation. Nevertheless, the problem of frequent interpretation and control errors associated with this display remains.

FIGURE AND GROUND

The problem of pilot errors on moving-horizon attitude displays may be explained in the context of the psychological phenomenon of figure and ground. Although figure-ground definitions emphasize static aspects of the visual field, dynamic aspects dominate the flight situation. Psychologically, the part of the field of view that appears to be stationary is customarily called the background, and the object that is moving is called the figure. When the entire visual field moves in relation to the observer's eye, as occurs with head movement, the observer usually perceives correctly that the background is stationary (Fitts and Jones 1961).

The question then becomes: do the figure and ground relationships between the aircraft and the outside world change when the pilot shifts attention from the outside world to the attitude indicator on the panel inside the cockpit? If the pilot's frame of reference changes when a small, abstract instrument representation of the outside world is all that is available, as opposed to the outside world itself, this change must involve a shift in the figure-ground relationship. Specifically, the aircraft's instrument panel or even the framed aperture of an individual display face becomes the background against which the display elements move.

The highly resolved, dynamic, literal image in full color presented on a display screen by a projection-type flight periscope consistently yields the same stable figure-ground relationships for all pilots regardless of display size (Roscoe 1948; 1951; Roscoe, Hasler, and Dougherty 1966). With display screens subtending visual angles ranging from 30 degrees down to 7.5 degrees (a 2-inch screen viewed from 15 inches) and presenting a forward looking view as narrow as 3.75 degrees (× 2 magnification), no control reversal was observed during more than 135 hours of flight experimentation involving more than 25 different pilots of widely varying experience.

CONTROL-DISPLAY RELATIONS

Motion compatibility must be considered in conjunction with the pilot's frame of reference. Depending on whether the desired or the actual position of a pilot's aircraft is the frame of reference, the display element may move either in the same direction or in a direction opposite to the control input. That is, the operator may consider the movement of a display symbol from the fixed reference either as an indication to be followed ("fly-to") or as something to be moved directly back to the fixed reference ("fly-from"). In the first instance a clockwise rotation of an artificial horizon symbol, indicating a left roll, would call for a clockwise rotation of the yoke to return to a wings-level attitude; in the second instance, clockwise rotation of an airplane symbol would indicate a right roll and would call for an opposite, or counterclockwise, response.

On careful examination it becomes apparent that the control reversal phenomenon is usually associated with a sudden response to a temporarily unnoticed change in attitude, such as a dropped wing caused by a gust of turbulent air or a banked attitude entered gradually while the pilot's attention is diverted. In routine maneuvers pilots have little trouble with the moving horizon. The problem seems to be associated almost exclusively with fast responses to slow changes in display indications; the critical consideration is that the elements of a display that respond immediately to the pilot's control inputs move in the expected direction.

FREQUENCY SEPARATION

These observations led to the idea of display frequency separation in which only the display elements that respond immediately to aircraft accelerations move in the same direction as the control inputs, and the more slowly moving indications of geographic position and flight attitude move in the contrary direction. The best known example of a frequency-separated display was introduced by Fogel (1959). Fogel's primary aim in the formulation of what he called a "kinalog" display (a contraction of "kinesthetic analog") was to make visually displayed attitude information more nearly compatible with the information a pilot receives through the kinesthetic and vestibular senses.

Fogel recognized that the labyrinthine or vestibular proprioceptors sense only accelerations and convey no direct information concerning rates or positions. Because accelerations in an aircraft, particularly the angular accelerations associated with changes in attitude, are typically transient in nature, Fogel reasoned that visual and vestibular compatibility requires only that the initial motion of a display indication from any steady state be in the same direction as the angular acceleration. Thereafter, the direction of display motion may gradually be reversed without conflicting with vestibular and kinesthetic cues.

For example, if the pilot moves the control to the right to initiate a right turn, the aircraft symbol should immediately rotate clockwise to coincide with the direction of angular acceleration. As the aircraft establishes its right turn and the angular acceleration is replaced by linear acceleration normal to the aircraft's wings, both the horizon line on the display and the aircraft symbol gradually rotate counterclockwise so that in a steady turn the aircraft's angle of bank is displayed by the tilt of the horizon bar, as in a conventional presentation.

A simple application of frequency separation to the presentation of aircraft attitude gives an immediate indication of roll acceleration and rate by the rotation of the airplane symbol in the same direction as the pilot's control inputs, while presenting attitude conventionally with a moving horizon symbol (Roscoe 1968; Johnson and Roscoe 1971). In effect, a predictive indication of bank angle is represented by the angle between the airplane and horizon symbols, and the quick response of the airplane symbol to control inputs is in the expected direction.

EXPERIMENTAL EVIDENCE

Pilot responses to various flight attitude and steering guidance display dynamics have been investigated systematically at the University of Illinois. Preliminary experiments (Johnson 1971; Johnson, Williges, and Roscoe 1971; Roscoe, Denney, and Johnson 1971; Jacobs, Williges, and Roscoe 1973) employed a Link GAT-2 general aviation trainer. Definitive experiments involving both flight-naive subjects and professional pilots performing a variety of flight and navigation tasks both in flight and in the Link GAT-2 have been reported by Ince (1973); Beringer, Williges, and Roscoe (1975); Ince, Williges, and Roscoe (1975); and Roscoe and Williges (1975).

Roscoe and Williges compared four attitude presentations in which either the horizon symbol or the airplane symbol, or both, moved relative to display coordinates in a flight experiment (Exhibit 7.2). Sixteen flight-naive Navy ROTC students each flew three different flight tasks in a Beechcraft C-45H under simulated instrument flight conditions following one hour of flight control orientation in a Piper Cherokee under contact flight conditions, with the flight attitude indicator covered. Subjects exhibited fewer control reversals during unknown attitude recoveries with the frequency-separated display than with the moving horizon display.

Although the moving airplane display produced the fewest reversals, disturbed-attitude tracking was inferior to that with either the moving horizon or frequency-separated displays (Exhibits 7.3 and 7.4). In the disturbed-attitude tracking task, subjects were required to compensate for displayed-attitude perturbations induced by band-limited (0.05 Hz) Gaussian noise summed with the actual bank attitude signal. The task forced subjects to follow visually presented attitude indications that were in continual dynamic conflict with their vestibular sensations of angular acceleration. Surprisingly, but perhaps not unaccountably, the moving airplane attitude presentation yielded reliably worse disturbed-attitude tracking than either the conventional moving horizon or its frequency-separated counterpart.

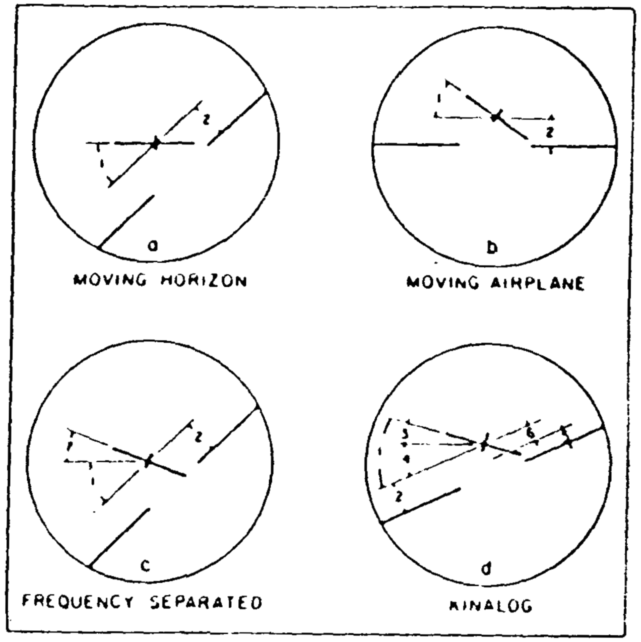

EXHIBIT 7.2. Experimental display configurations used in the disturbed-attitude tracking task. 1 = displayed bank angle (command bank minus actual bank). 2 = pitch angle; 3 = displayed bank minus lagged displayed bank; 4 = lagged displayed bank; 5 = pitch minus lagged pitch; 6 = lagged pitch; 7 = aileron position *(Roscoe and Williges 1975)*

Display Type	Reversed Responses	Correct Responses	Total Trials
Moving horizon	14	50	64
Moving airplane	3	61	64
Frequency separated	9	55	64

EXHIBIT 7.3. Control reversals and correct responses made with and without knowledge of display type by 16 subjects each attempting to recover from four subliminally entered unknown attitudes while using each of three types of attitude presentation in flight *(Roscoe and Williges 1975)*

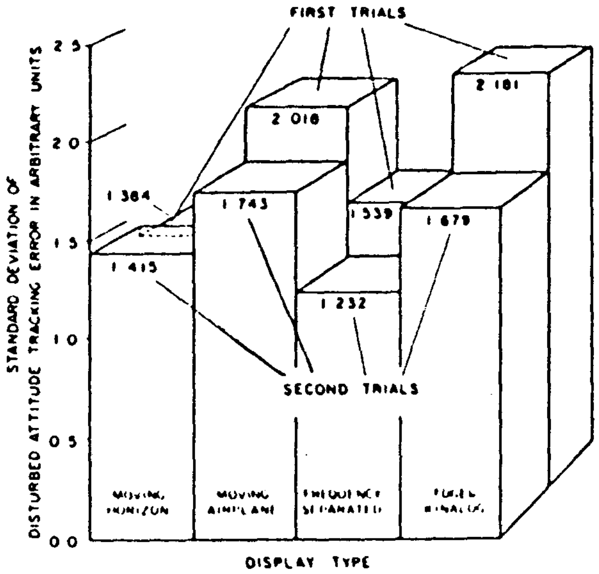

EXHIBIT 7.4. Mean standard deviation of disturbed-attitude tracking error in arbitrary units for 16 subjects as a function of display type and tracking trial *(Roscoe and Williges 1975)*.

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This single unprecedented finding casts doubt on the validity of the results of numerous experiments in fixed-base and moving-base simulators that have indicated superior performance with moving airplane attitude displays (Browne 1945; 1954; Loucks 1947; Nygaard and Roscoe 1953; Roscoe, Wilson, and Deming 1954; Dunlap and Associates 1955; Bauerschmidt and Roscoe 1960; Weisz et al. 1960; Matheny, Dougherty, and Willis 1963; Johnson, Williges, and Roscoe 1971; Jacobs, Williges, and Roscoe 1973).

The inferior performance with the moving airplane attitude presentation cannot be attributed to conflict between visual and vestibular cues because the disturbed-attitude tracking task created serious cue conflict with all displays tested. In all cases, good performance required the subject to ignore vestibular acceleration cues and respond only to the visual presentation. The inferior performance with the moving airplane display must be accounted for in terms of one or more possible alternative causes.

A within-subject design was used in this study; all subjects were tested on all displays in counterbalanced orders. Poulton (1969) has suggested that differential transfer effects among experimental conditions can bias comparative results in experiments of this type. In this experiment, differential transfer may well have occurred because a disproportionate amount of practice was received on what were basically moving horizon presentations. The frequency-separated display is identical to the moving horizon display except for the predictive roll-rate indication superposed on the aircraft symbol, and the kinalog display exponentially decays to a moving horizon presentation with a 5-second lag.

Consequently, each subject, all of whom were male nonpilots, received three-fourths of his practice on moving horizon type displays and one-fourth on the single moving airplane attitude presentation as he progressed through his particular testing sequence in the counterbalanced design. The fact that both the frequency-separated display and the kinalog display exhibited limited aircraft symbol movement would tend to offset this postulated biasing effect.

To test the possibility that the apparent inferiority of the moving airplane display may have been due to differential transfer, two additional analyses of the disturbed-attitude tracking data were performed. First, the four attitude presentations were compared on the basis of performance on the four occasions in which each was flown first in the counterbalanced design to eliminate any transfer effect. Second, the data were analyzed with sequence of testing as a factor, and performances with the first display flown were compared with average performances on displays flown in the second, third, and fourth serial positions in the counterbalanced sequences.

Average standard deviations of disturbed-attitude tracking errors for the first and second trials on the first display flown by each subject are summarized in Exhibit 7.5. Although the apparent differences were not statistically reliable, the mean performances for the independent groups of four subjects each who flew with the moving horizon and moving airplane displays, respectively, differed in the direction predicted by the hypothesis that the reliable overall inferiority of the moving airplane presentation is a reflection of differential transfer within the counterbalanced design.

By considering only performances on the first display flown, the attitude presentation factor becomes a between-subjects factor, and only 4 subjects rather than 16 appear in each treatment. For this relatively insensitive analysis, more data would be necessary to determine the possible reliability of the apparent initial superiority of the frequency-separated display. It would appear, however, that future experiments of this type should employ between-subjects designs to avoid possible differential intraserial transfer effects. Naturally, for tasks in which there is no a priori reason to suspect biasing intraserial effects and no pretest evidence thereof, the thrifty investigator need not forgo the economies of within-subject designs.

The results of the supplementary breakdown of serial position effects are shown in Exhibit 7.6. By assuming serial positions and display types to be between-subjects variables (as are the several combinations of these variables), a reliable Trial × Serial Position × Display Type interaction was present ($p < 0.05$). The means for this interaction again show a

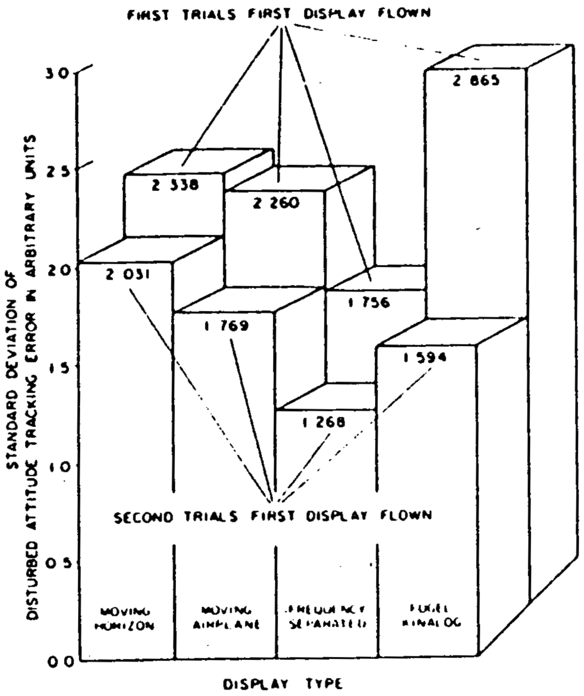

EXHIBIT 7.5. Mean standard deviation of disturbed-attitude tracking error in arbitrary units as a function of display type and trial for the first display flown by subgroups of four subjects each *(Roscoe and Williges 1975)*.

Serial Position	Trial	Display Type Moving horizon	Moving airplane	Frequency separated	Fogel kinalog
1	1	2.34	2.26	1.76	2.87
	2	2.03	1.77	1.27	1.59
2	1	1.07	2.08	1.20	1.92
	2	1.12	1.81	1.01	1.61
3	1	1.15	1.34	1.92	1.91
	2	1.22	1.77	1.33	1.63
4	1	0.98	2.39	1.28	2.03
	2	1.29	1.63	1.32	1.88

EXHIBIT 7.6. Mean standard deviation of disturbed-attitude tracking error in arbitrary units for two trials by subgroups of four subjects on each of four display types across four serial positions *(Roscoe and Williges 1975)*.

marked improvement with the moving horizon display following relatively poor performance in the first serial position. With the exception of the disproportionately poor first-trial performances with the kinalog display, serial position did not systematically affect performances on the other three displays.

Ince, Williges, and Roscoe (1975) closely replicated the procedures of the flight experiment using 24 flight-naive subjects in the Link GAT-2 simulator. Independent groups of 8 subjects each were tested on the various display configurations and tasks while flying, respectively, with no cockpit motion, the sustained cockpit motion normal to the GAT-2, and subliminal "washout" motion. The frequency-separated display produced disturbed-attitude tracking performance superior to all other displays across all motion conditions tested (Exhibit 7.7). Furthermore, unknown attitude recovery times were reliably shorter for the frequency-

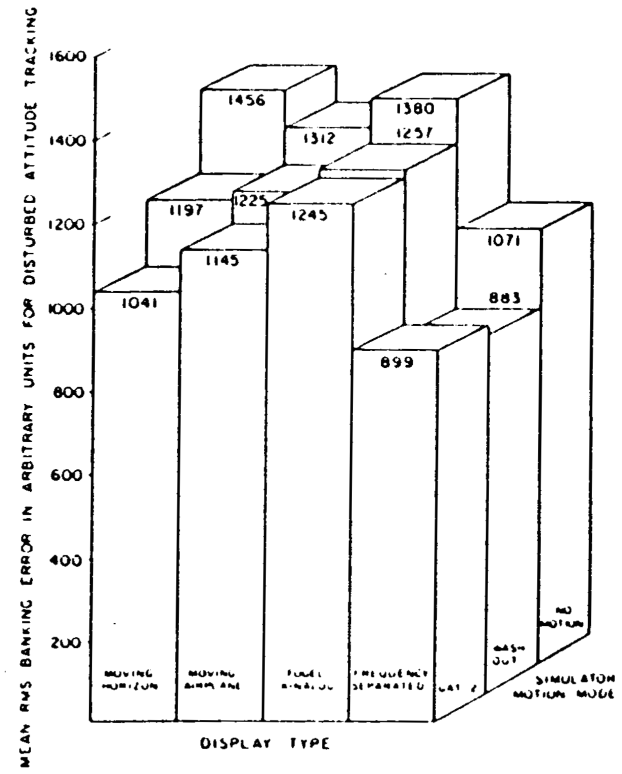

EXHIBIT 7.7. Mean RMS banking errors in arbitrary units for disturbed-attitude tracking by independent groups of eight subjects in each simulator motion mode as a function of display type *(Ince, Williges, and Roscoe 1975)*.

separated display than for the moving horizon and moving airplane displays in the simulator.

Comparison of the three displays in terms of control reversals generally supported the conclusion that the superior response stereotype of the moving airplane display repeatedly found in simulation experiments also holds in flight. Because the idea of a frequency-separated attitude presentation was originally put forth as a means of gaining the reversal-preventing benefits of the control-compatible moving airplane symbol without interfering with pilots' overlearned use of the moving horizon, the results for initial responses obtained in these experiments afford little comfort.

However, initial control reversals are usually caught and corrected, often going unnoticed by others in the cockpit. Reversals that go undetected and uncorrected, or secondary reversals made in confusion following an initial response, may be the ones that more often prove fatal. Secondary reversal results, particularly those for washout motion, offer some comfort because the surprisingly high frequency of secondary reversals with the moving horizon display (2 in every 10 recoveries) were cut by two-thirds with the frequency-separated display, approximately the same as with the moving airplane display.

The results of these studies suggested that the frequency-separated display provides comparable and in some cases superior performances by relatively inexperienced pilots to those obtained with the moving horizon display. However, adoption of a frequency-separated attitude presentation for general use would necessarily require a consideration of its possible adverse effects on the overlearned response stereotypes of experienced pilots. Furthermore, the acceptance of the frequency-separated presentation by senior pilots might depend on whether they viewed it as a completely new display or as a refinement of a familiar one.

Beringer, Williges, and Roscoe (1975) extended the investigation to independent groups of eight professional pilots each. The pilots' performances were measured during their initial transitions to their respective displays in the Link GAT-2 and the Beechcraft C-45H. Disturbed-attitude tracking performances in the airplane were reliably better with the frequency-separated display than with either the conventional moving horizon or the moving airplane presentation (Exhibit 7.8). Performances followed the same pattern during the pilots' initial introduction to their respective experimental displays in the simulator, but the differences were smaller and not statistically reliable.

Performances with the frequency-separated and moving horizon displays were superior to those with the moving airplane display in speed of recovery from unknown attitudes in the airplane. Examination of control input latencies and subsequent maneuvering times indicated that the differential speeds of recovery were due to differences in maneuvering rates during recovery, not to differential speeds of initial response when presented with unknown attitudes. The extremely low incidence of control reversals by the professional pilots during their second series of trials with all displays was consistent with their uniformly deliberate initial responses.

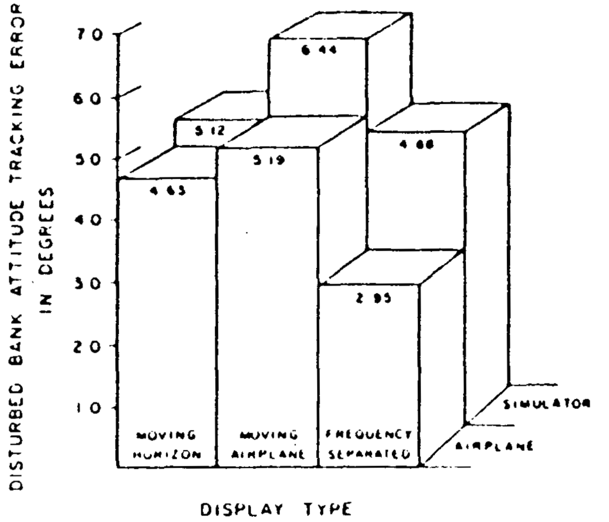

EXHIBIT 7.8. Mean RMS banking errors in degrees for disturbed-attitude tracking by independent groups of eight pilots using each display in the Link GAT-2 and Beechcraft C-45H *(Beringer, Williges, and Roscoe 1975)*

Performances with the frequency-separated display on both tasks may be partially attributable to its "command indicator" nature which provides a "programed" return to a wings-level attitude, minimizing the probability of overshoot. The serendipitous command guidance provided by the frequency-separated presentation occurs as a by-product of the fact that the aileron position signal was precisely scaled to yield the proper roll rate schedule for a fast, exponential recovery to a wings-level attitude simply by maintaining alignment of the airplane symbol and the horizon line. The speed of recovery is directly dependent on the scale factor selected: the more sensitive the aileron position indication, the slower and smoother the recovery; the less sensitive, the faster and rougher. The optimum choice yields a fast but stable recovery.

REVIEW OF THE ISSUES

Several basic questions were posed by Johnson and Roscoe (1972) concerning motion relationships in aircraft attitude displays. One concern was the speed with which flight-naive and relatively inexperienced pilots learn to use the frequency-separated display. Experiments with this subject population (Jacobs, Williges, and Roscoe 1973; Ince, Williges, and Roscoe 1975; Roscoe and Williges 1975) have shown performance with the frequency-separated display to be comparable if not superior to that obtained with the moving horizon display. In no case has there been evidence of greater difficulty in learning the motion relationships of the frequency-separated presentation. The disturbed-attitude tracking task actually showed a reliable superiority of the frequency-separated display.

If a display is to be considered for general use, one must take into account all segments of the pilot population that will be affected. This requires that the transition of highly experienced pilots from the moving horizon to any other display format be examined. Beringer, Williges, and Roscoe (1975) investigated this question, and the results suggest that highly experienced pilots can easily learn to use the frequency-separated attitude display and, for some tasks, may be expected to perform better with it.

Another requirement was the use of operationally realistic and difficult flight tasks. The area navigation task, paired with a concurrent number-cancelling adaptive side task, provided such a context, at least in terms of realism and difficulty of workload demands. Although there were no reliable differences among the three attitude presentations in terms of altitude and course errors or residual pilot attention, the minor sample differences observed favored the frequency-separated display.

Both disturbed-attitude tracking and recoveries from unknown attitudes exposed pilots to conflicting visual and vestibular cues in a manner conducive to control reversals and spatial disorientation. Comparing data obtained in the simulator with data obtained in the airplane in this series of experiments, corresponding results are generally comparable when the simulator is operated with washout cockpit motion. Instances in which differences occurred may be attributed to the absence of cockpit motion, inappropriate motion cues, or specific differences in flight dynamics between the simulator and the airplane.

The results of the study of flight transition of professional pilots to frequency-separated attitude display, together with the results of earlier experiments involving subjects with little flight experience, place the new display in a unique position. Nonpilots and pilots of little experience readily learn to use it and show little tendency toward control reversals to which inexperienced pilots are subject with the conventional moving horizon. Highly experienced pilots readily adapt to it as a moving horizon display to which only a roll-rate prediction has been added to assist them in maneuvering the airplane.

With these attributes in mind, it would appear that the frequency-separation principle, used in conjunction with the flight path prediction principle to be discussed in Chapter 8, is an ideal candidate for use both by pilots in training and by those with higher levels of experience. The remaining step in the acceptance of a frequency-separated flight attitude and steering guidance display is its routine use in both training and operational applications for a sufficient period to expose and correct any undetected problems prior to its general adoption.

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Aircraft Attitude Awareness From Visual Displays

Robert M. Taylor

RAF Institute of Aviation Medicine

Farnborough, Hampshire, UK

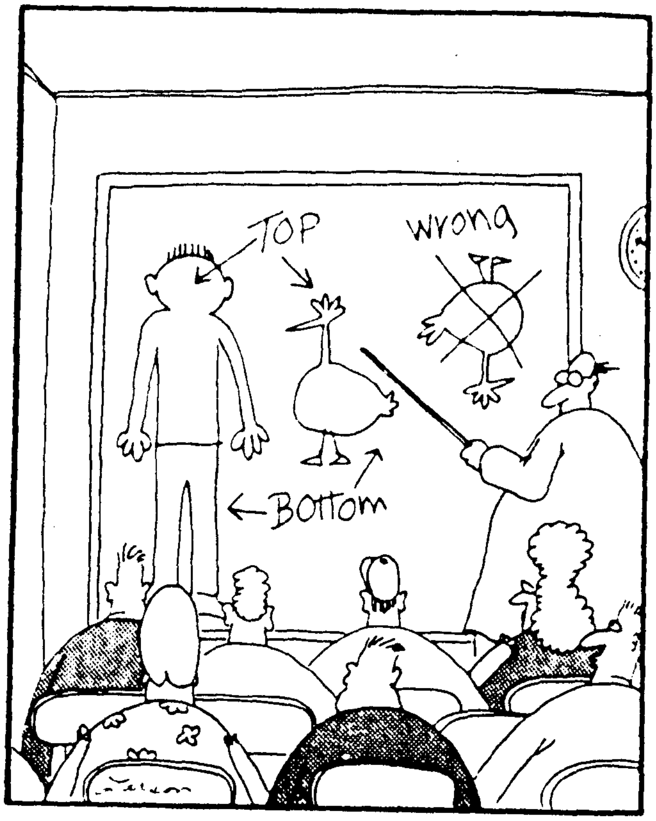
Biography

Robert M. Taylor

Born in Bradford, Yorkshire and educated at Presentation College, Reading and at the Unversity of London, from which he graduated in 1970 with a BSc Honours Degree in Psychology. After graduating, he took up a research appointment with the Cival Service at the Royal Air Force Institute of Aviation Medicine, Farnborough where he is now a Principal Psychologist in the General Psychology Section.

AIRCRAFT ATTITUDE AWARENESS FROM VISUAL DISPLAYS

Robert M. Taylor
RAF Institute of Aviation Medicine
Farnborough, Hampshire, UK



For people who don't know which way is up.

SUMMARY

Rapid appreciation of spatial orientation is essential when recovering from unusual attitudes during aircraft combat and emergency manoeuvres. This paper is concerned with attitude awareness derived from aircraft instruments, in particular the comprehension of pitch, roll and horizon information from head-up displays. Human visual orientation is discussed with respect to dual-mode theory of focal and ambient visual information processing, with particular emphasis on the perception of pattern orientation and the relative contributions of global and local features in multi-dimensional structures. It is argued that global organisational characteristics of display formats are important and neglected sources of cues for attitude awareness. An improved pitch scale symbology for head-up displays is proposed based on empirical evidence from studies of operator performance on unusual attitude recovery tasks.

SPATIAL ORIENTATION AND ATTITUDE AWARENESS

In recent years, an increasing proportion of human factors accidents and incidents in high performance aircraft have been attributed to spatial disorientation or loss of attitude awareness. A major factor contributing to this trend is that whilst developments in airframe construction and electronic flight controls systems have improved aircraft agility and manoeuvrability, they have also reduced the noise and vibration cues to attitude changes. This has increased dependence on visual information for detecting undemanded attitude changes and added a further onus of responsibility on information design for an already heavily burdened sensory channel.

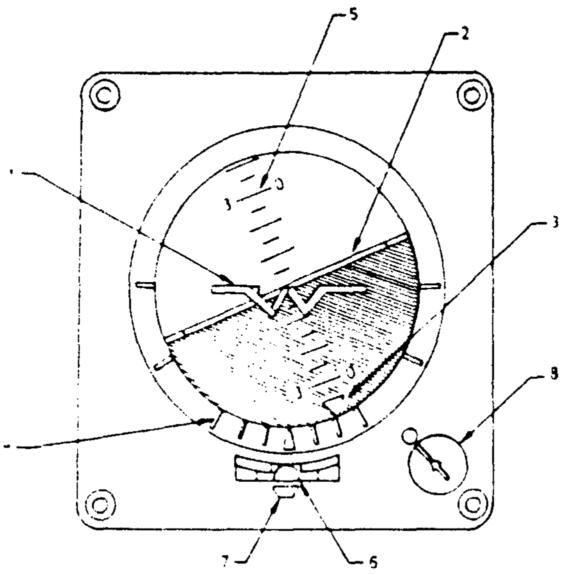
In examining the requirement for visual information on aircraft attitudes, a useful distinction can be drawn between the normal process of maintaining spatial orientation, and the processes of recognising disorientation and recovering pitch and bank angle control from unusual attitudes. Dual-process theory of human visual orientation (LEIBOWITZ and POST, 1982) suggests that orientation in visual flight rules (VFR) conditions is mostly maintained through detection of peripheral horizon and retinal motion, optic flow cues (c.f. GRINDLEY, 1942; GIBSON, 1979) processed sub-cortically without conscious attention or awareness. This system is known as the ambient mode of processing. The ambient system is served by the large para-foveal areas of the retina which are sensitive to low spatial frequency information. Information from the ambient system is integrated with vestibular and somatosensory inputs at a sub-cortical level for the maintenance of spatial orientation, posture and stability of gaze. This relatively primitive, unintelligent mode of processing produces the

fields. Orientation information can also be obtained through the focal processing system. The focal system is served by the fovea, the small central part of the retina concerned with the resolution of high spatial frequency information. Information from the fovea projects directly on the visual cortex. The focal system is the cognitive mode of processing involved in the recognition of objects and patterns at the focus of visual attention. It is this system which is used to provide spatial orientation and attitude awareness in instrument flight rules (IFR) conditions.

It follows from dual-process theory that disorientation tends to occur in the VFR-IFR transition where there is a reduction in ambient cues, at unusual attitudes during combat and emergency manoeuvres where the familiar ambient cues are rapidly changed, and during periods of distraction and inattention when flying on instruments without ambient cues. The extent to which maintaining spatial orientation is either a conscious or automatic process will depend on the relative contributions of focal and ambient mode processing. Recognising disorientation, recovering from unusual attitudes and achieving highly resolved pitch and bank angle control are more clearly conscious deliberate cortical activities, involving focal rather than ambient mode processing resources. Rapid appreciation of spatial orientation and immediate corrective action using rules and heuristics, such as "roll and pull to the nearest horizon", are essential requirements for recovering from unusual attitudes in limited airspace. In these circumstances, display design factors affecting the comprehension of pitch, roll and horizon information will be of paramount importance. Indeed, the task of unusual attitude recovery provides a critical test of design efficacy and a potentially more decisive analytical tool than evaluation of attitude control performance.

ATTITUDE INDICATORS

An international design standard exists for military electromechanical attitude instruments (NATO STANAG 3637 - Attitude Indicators). According to this agreement, the standard Attitude Indicator (AI) comprises an horizon bar, roll (bank) pointer and pitch reference scale displayed on a gyro stabilised sphere representing the outside world (Fig. 1). Colour coding is used to distinguish above horizon, positive pitch angles (light 'sky' colour) from below horizon, negative pitch angles (dark 'ground' colour). A symbol representing the aircraft, fixed with respect to the instrument panel, is located over the centre of the sphere. A fixed bank scale is shown on the sphere surround. This representation conforms to the appearance of the natural horizon viewed through a hole in the instrument panel, providing an "inside-looking out" contact-analog display with the advantages for comprehension of pictorial realism. The original 1920's Sperry Horizon, used in the fog flying exploits of James Doolittle, embodied these basic elements. Now the contact-analog AI is widely used throughout aviation. Longevity and widespread use have made it an extremely robust design standard, highly resistant to change, a not uncommon characteristic of long-established design customs (the QWERTY effect?). Indeed most advanced colour electronic head-down displays (HDDs) mimic this format.



1. Miniature Aircraft
2. Horizon Bar
3 Bank Pointer
4 Bank Scale
5. Pitch Reference Scale
6. Slip/Skid Indicator
7 Rate of Turn Indicator
8. Pitch Trim Knob

Fig. 1 NATO STANAG 3637 Attitude Indicator.

The concept of the contact-analog AI was challenged by RUFFELL-SMITH in 1948 (RUFFELL-SMITH, 1948). He described an attitude indicator with separated pitch and roll presentations, attributed to HONICK of the Royal Aircraft Establishment (Fig.2). Separate displays were proposed to provide more accurate resolution of pitch and roll information in the belief that humans were better at integration than differentiation. However, subsequent comparative evaluation of separated and integrated displays using an unusual attitude recovery task produced mixed results (BURROWS and CAMERON, 1957). Needless to say, the argument for separated displays did not prevail. Separate attention to pitch and roll is probably not necessary for practical flight control. Most contact-analog AIs with an integrated representation provide separate pitch and roll scales for independent reference if needed.

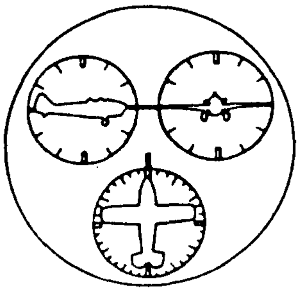


Fig. 2 HONICK Attitude Indicator (from RUFFELL-SMITH 1948)

Other empirical studies have challenged the appropriateness of the movement relationships of the contact analog AI for unusual attitude recovery (FOGEL, 1959; JOHNSON and ROSCOE, 1972; ROSCOE, CORL and JENSEN, 1981). It has been argued that the contact-analog representation should enable the same highly learnt set of rules to be used for control responses to changes in both the natural and artificial horizon. However, evidence indicates that at unusual attitudes response hesitancy and control reversals are more common with standard AIs than in AIs where the horizon is fixed and the aircraft symbol moves with respect to the instrument panel, i.e. an "outside-looking-in" reference. These effects are interpreted as caused by ambiguity in the movement of the display elements and the perception of inappropriate figure-ground relationships. During visual flight, the aircraft is correctly perceived as the moving element or figure and the outside world as the fixed element or ground (orientated perception). During instrument flight, it is possible to perceive the stabilised horizon bar as the moving element or figure and the aircraft symbol and instrument surround as the fixed ground (disorientated perception). The erroneous perception of the horizon as the moving figure trips inappropriate movement-compatible control inputs or control reversals. The change in figure-ground perception is attributed to the low saliency of the artificial horizon viewed against the larger and perceptually more stable cockpit framework, compared with the dominant stability of the natural horizon. Empirical studies have shown that control errors can be reduced by allowing the aircraft symbol to move briefly in the same direction as the control for small fast responses, before moving the horizon in the opposite direction for large slow responses (INCE, WILLIGES and ROSCOE, 1975; BERINGER, WILLIGES and ROSCOE, 1975; ROSCOE and WILLIGES, 1975). This is known as the principle of frequency-separation (FOGEL, 1959).

In 1944, recognising the figure-ground problem, K. CRAIK proposed that the representation of the artificial horizon should be enlarged to increase its saliency and perceived stability (BROWNE, 1954). Increasing the size of the horizon also provides a more sensitive index of pitch and bank angle by changing the scaling factor. Empirical studies with cathode ray tube (CRT) AIs have shown that performance improves with increasing horizon length up to that obtained on a 280 mm (11 in) CRT, offering a 12-21^{o} horizon visual angle (CROSS and BITTNER, 1969). Larger horizons produced a performance deterioration. SEMPLE, HEAPY and CONWAY (1971) suggest that this deterioration could be due to difficulty integrating attitude information over large areas. In practice, despite this evidence, standard AIs have become smaller rather than larger without frequency separation. A typical 122 mm (5 in) AI has a sphere diameter of 76 mm. Standard cockpit CRT sizes place similar limitations on horizon bar length.

A variety of peripheral vision attitude indicators have been produced to overcome the size limitations of AIs with little commercial success. These include the Smiths Para-Visual Director or PVD (MAJENDIE, 1960) and the Collins Peripheral Command Indicator or PCI (FENWICK, 1963), both of which provide "barber's pole" vection cues, and more recently, the Malcolm Horizon or Peripheral Vision Horizon Display or PVHD (MONEY, MALCOLM and ANDERSON, 1976). The PVHD projects an extended horizon line through the AI and across the instrument panel using a rapidly scanning laser light spot. This provides horizon orientation rather than vection cues.

Comparative evaluations of peripheral devices have produced mixed results (BROWN, HOLMQVIST and WOODHOUSE, 1961; VALLERIE, 1966; HASBROOK and YOUNG, 1968). It can be argued that these devices attempt to provide artificial stimulation to the ambient visual system (MALCOLM, 1984). However, the extent to which peripheral displays function as an ambient stimulus is difficult to measure directly and has to be inferred from apparent loading of attentional resources. A successful ambient display would free attentional resources for other tasks. Existing displays offer relatively isolated peripheral movement cues which are inherently attention-getting against an otherwise mostly stable background, and generate only a marginally adequate ambient stimulus. In theory, an effective ambient display should reduce the incidence of disorientation. However, ambient processing is unlikely to provide the highly resolved pitch and bank angle control necessary for precision manoeuvres, nor is it likely to assist in unusual attitude recovery which involves focal attention and the conscious application of rules and heuristics such as "roll and pull to the nearest horizon". An integrated combination of focal and ambient displays would provide a more comprehensive solution.

HEAD-UP DISPLAYS

The general trend in military cockpits has been to provide electronic head-up displays (HUDs) as the primary attitude reference superimposed on the outside-world. This approach goes some way towards an integration of focal and ambient information. HUDs use different coding methods than AIs and HDDs to represent aircraft attitude. Area colour coding is inadmissable on superimposed displays because of the need to minimise obscuration of the outside word. Instead, abstract, symbolic codes are used that rely on lines, shapes and numerals for pitch, roll and horizon information without the advantages for comprehension of pictorial realism. Conventional AIs are provided as alternative independent sources of attitude information and as secondary, standby or reversionary instruments.

Ideally, HUDs, HDDs and AIs should use identical coding methods for displaying attitude information. Coding differences place demands on cognitive processing that lead to difficulties in attention-switching, cross-monitoring and reversion, contributing further to the problems of maintaining and recovering attitude awareness (SCHMIT, 1982). Attention-switching between HUDs and AIs has been made increasingly difficult by the trend for smaller AIs located in low, inaccessible positions in the cockpit. Valuable visual panel space immediately beneath HUDs is taken up by HUD control panels and data-entry keyboards. Using this space for important visual information, such as a reversionary attitude display, would seem to be a more logical and safer arrangement.

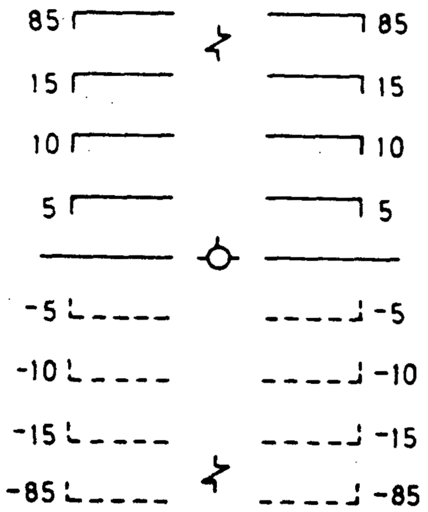


Fig. 3 MIL-STD-884 Symbology

Unlike AIs, there is no international standard for HUD symbology. A US Military Standard (MIL-STD-884) suggests for guidance the generic symbols in Fig. 3, with the intention that specific requirements should be tailored to meet individual needs. The recommended attitude symbology comprises a central horizon line with parallel lines for pitch angles to +90° (zenith) and -90° (nadir). The instantaneous field-of-view or IFOV (10-20°) usually limits the display to three visible pitch lines. A fixed central symbol represents the aircraft's velocity vector or fuselage datum. In flight, the stabilised pitch scale appears to move with reference to the aircraft symbol, rotating to indicate roll, and translating to indicate pitch, i.e. inside-looking-out display. The preferred movement gearing is usually 1:1 with respect to the outside world, superimposing the horizon line on the natural horizon. Some HUDs have slowed pitch movement (e.g. 1:3) at high pitch angles ($>30^{\circ}$), where the horizon is outside the field-of-view, to facilitate comprehension during rapid pitch rate changes.

Surveys have revealed wide variations in HUD symbology with little empirical evidence to support compliance with standards (e.g. GREEN, 1977; EGAN and GOODSON, 1978; NEWMAN and FOXWORTH, 1984). Fig. 4 shows a HUD pitch scale with 1:3 pitch gearing developed for the UK Harrier and Jaguar aircraft. Differences from MIL-STD-884 in Fig. 3 include the coding of positive and negative pitch lines, the location and direction of vertical tags on pitch lines, the positioning of pitch scale numerals, and occlusion of the aircraft tail fin. No documented rationale has been given for these differences and no substantial differences in information requirements would account for the variations. Indeed, as far as can be determined, the symbology differences have arisen through independent evolutionary design processes. Typically, these processes rely on trial-and-error and subjective assessments, with little systematic analysis of information requirements and little empirical testing of operator performance. Subjective judgements are strongly influenced by past experience and vary in consistency and reliability particularly when concerned with verbal knowledge of skilled performance (BERRY and BROADBENT, 1984). Unfortunately, the substantial empirical evidence on operator performance with electro-mechanical instruments cannot be readily generalised to superimposed electronic displays. Original empirical studies are needed to support symbology standardisation and more importantly, to provide a theoretical foundation for predicting the effects of design changes.

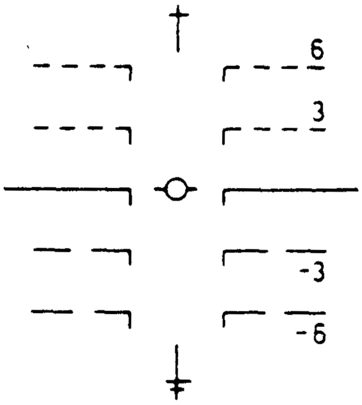


Fig. 4 **Jaguar/Harrier Symbology**

ORIENTATION AND SHAPE PERCEPTION

Design guidance for HUD symbology as focal mode stimuli can be found in the characteristics of natural objects and patterns that facilitate orientation judgements and shape perception. Natural objects usually maintain a constant orientation to the direction of gravity. Normally, recognition is achieved by keeping the head and eyes upright. Recognition is disrupted when objects are not in their normal orientation, e.g. Fig. 5. Here, recognition is achieved by mental rotation or normalisation. It has been demonstrated that recognition latency increases as a function of the amount of rotation required for normalisation (SHEPARD and METZLER, 1971).

Fig. 5 Inversion disrupts recognition. Global features mask local distortions. (with apologies to Dr John Rolfe, FRAeS, Senior Principal Psychologist, MOD).

Most natural objects have features that are recognised regardless of orientation or are coded in an orientation-free form, such as colour and texture. These act as polar features distinguishing top and bottom, and indicate tilt, orientation and the normalisation required (HOWARD, 1982). The position of the centre of gravity of an object, which is normally low, can be regarded as a polar feature. Hence, shapes that taper upwards are more often judged as upright. Upright shapes tend to have dominant detail at the top (e.g. heads on bodies) and exhibit a surface texture gradient with smaller detail at the top, furthest from the point of regard.

Most HUD pitch scales use symbols to designate the zenith and nadir poles, e.g. Fig. 4. These are only visible at extreme pitch angles on HUDs with 1:1 pitch scaling, and never appear concurrently in the field-of-view. At low pitch angles, with the horizon visible, the symbols for positive and negative pitch angles provide polar features above and below the horizon, serving the same function as sky/ground colours on AIs. At intermediate pitch angles, when only positive or negative pitch lines are in view, polarity is indicated only in the structure or shape of the individual pitch lines and pitch scale numerals. Research has shown that current HUD symbology lacks natural, intuitively meaningful polar cues. Judgements of the orientation of typical pitch scale segments by naive observers are inconsistent and unreliable (TAYLOR, 1982). In practice, experience and training are the primary determinants of the perception of pitch scale orientation rather than intuitive responses to natural polar cues.

For reasons already discussed, it is possible to perceive either the HUD pitch scale or the aircraft reference symbol as the moving figure. Since it is only appropriate to perceive the aircraft as the moving figure, it may be important that the aircraft symbol as well as the pitch scale should have features to indicate orientation and uprightness. The standard symbol looks like the shape of an aircraft viewed from the rear, formed by a circle with horizontal tags or wings and a vertical tag or tail fin, e.g. Fig. 3. The vertical tag serves as a distinctive polar feature for orientation. On the Jaguar and Harrier HUDs, the symbol is referenced to the aircraft's climb-dive angle (CDA). The fin serves as a CDA limit indicator and it is normally occluded when the CDA is within limits, e.g. Fig. 4. The occlusion of the tail fin has not been criticised by aircrew but like most design features, there is no empirical evidence to support either its inclusion or occlusion.

In natural objects and patterns, the line joining any pair of polar features, known as the polar axis, can indicate which way an object is tilted, whether erect up or inverted. On HUD pitch scales, this is an imaginary line, joining the zenith and nadir running through the aircraft reference symbol and perpendicular to the horizon. Other axes that help judge the orientation of objects include the following: axes of balance, which run through the centre of gravity perpendicular to the base; axes of symmetry, which divide the shape into identical mirror-image halves; and main lines axes, which predominate the object or shape, often but not always parallel to the axes of symmetry. If the mass is evenly distributed, then all axes of symmetry are axes of balance. The position of an axis of symmetry is usually relatively easy to judge, making it a particularly salient axis of balance. A heavy reliance is placed on axes of symmetry when judging whether an object or shape is tilted. It follows that HUD pitch scales should be designed with coincident or parallel polar axes, main line axes, axes of symmetry and balance.

MULTI-DIMENSIONAL STIMULUS PROCESSING

Other important perspectives, offering a rich source of design guidance, come from the literature of cognitive psychology concerning the processing of complex multi-dimensional stimuli. In this approach, the perception of complex patterns is considered in terms of the relative contributions of global and local features, and the existence of integral and separate stimulus structures. There is converging evidence that as a general rule the global characteristics of complex multi-dimensional visual stimuli are processed faster than local detail unless the quality of the information at the global level is particularly poor (MARR, 1976; NAVON, 1977; HUGHES et al, 1984). Fig. 5 demonstrates how global similarities can mask local differences. Given this, it would seem reasonable to conclude that for tasks requiring rapid decision-making, such as HUD attitude recovery, the emphasis in design should be on the quality of the global characteristics of display formats as well as on their detailed content. Unfortunately, it is probably true that the quality of information on HUDs at the global level is relatively poor. Much information is represented by local features such as pointers and digital readouts. Some guidance on the desirable perceptual characteristics of such formats can be obtained from studies of the principles of perceptual organisation identified by Gestalt psychologists (KUBOVY and POMERANTZ, 1981). Formats that conform to Gestalt laws of proximity, similarity, closure, good continuation and symmetry should be more coherent, easier to work with and able to communicate the necessary information more effectively than formats that do not possess these qualities.

A further separate but not unrelated perspective that can be drawn upon is the notion that the HUD format has a multi-dimensional structure which affects both what is processed and the way in which it is processed. Two kinds of multi-dimensional stimulus structure are distinguished: structures with integral stimulus dimensions and structures with separate stimulus dimensions (GARNER, 1974). Integral structures are processed and perceived as simple, unified, coherent wholes; others are processed and perceived as divisible stimuli with separate discriminable stimulus dimensions. Colour is a prime example of an integral structure having the relatively indivisible dimensions of hue, brightness and saturation. Redundant dimensions are sometimes used in display design to emphasise important information. According to the integrality notion, only integral dimensions are capable of producing redundancy gain performance improvements for correlated dimensions or interference for orthogonal dimensions, compared with uni-dimensional stimuli. The distinction is analogous to parallel and serial processing of multi-dimensional stimuli. In integral structures, the individual dimensions are processed in a parallel rather than serial manner. The combination of separate non-integral stimulus dimensions leads to performance improvement only if the additional dimensions are more easily discriminated and processed faster. The presence of poorly discriminated non-integral dimensions may attract unnecessary attention, increase response latencies, reduce the saliency and discriminability of more effective cues, and cause undesirable clutter and obscuration of the outside-world. For similar reasons, non-integral contingent dimensions, where the meaning of a given cue is dependent on another, are less effective than integral or uni-dimensional symbols. Using a speech analogy, integral multi-dimensional structures articulate clearer and louder; separate redundant multi-dimensional structures merely repeat the message; non-integral contingent structures simply take longer to complete the communication.

The Gestalt laws predict the structures and organisations that will be perceived as coherent groups or figures in HUD formats. For good design, the most readily perceived structure should conform with the functional organisation of the information. An application of the grouping concept in the USAF F105 D aircraft is illustrated in Fig. 6, attributed to SIGFRIED KNEYMEYER of the Wright Air Development Centre. This arrangement is known as the USAF Integrated Cockpit Display or "T" scan Peripheral Command Indicator (WULFECK, WEISZ and RABEN, 1958). Altitude, airspeed and Mach-number are displayed by moving vertical scales. Preset command values become horizontally aligned with the horizon in normal flight and provide a common centre line across all the instruments. The pilot flies to keep all the indices aligned across the reference line without having to remember specific values. Scale displacements are as far as possible in a single direction and consistently related to the centre reference line and the pilot's control movement. For instance, pulling the stick backwards to climb causes the horizon, command indices and associated tapes all to move down. Fig. 7 depicts HUD attitude symbology used on RAF aircraft with similar organisational characteristics. An angle-of-attack (AOA) scale is depicted on the left, a vertical speed scale on the right, and a heading scale below the attitude symbology. Two conditions of flight are shown. In the normal condition (level flight, low AOA, and vertical speed), the configuration is simple and symmetrical with horizontal and vertical alignment of the displayed elements. At unusual attitudes, the configuration is relatively complex, asymmetrical and disintegrated, facilitating attention to parts with increased saliency for the AOA and vertical speed presentations. In this design, the attentional integrative load is reduced during normal conditions, facilitating recognition of the desired configuration, and a distinctively dissimilar configuration is used to announce unexpected attitudes. The penalty for this approach is that during controlled flight through unusual positions, maintaining an integrated holistic awareness of the aircraft's attitude and direction of movement draws considerably on attentional resources.

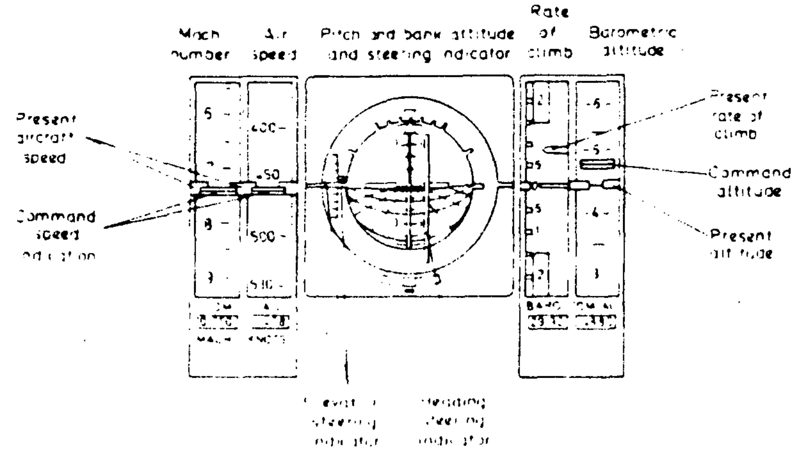


Fig. 6 Early USAF Integrated Cockpit Display
(from WULFECK et al, 1958)

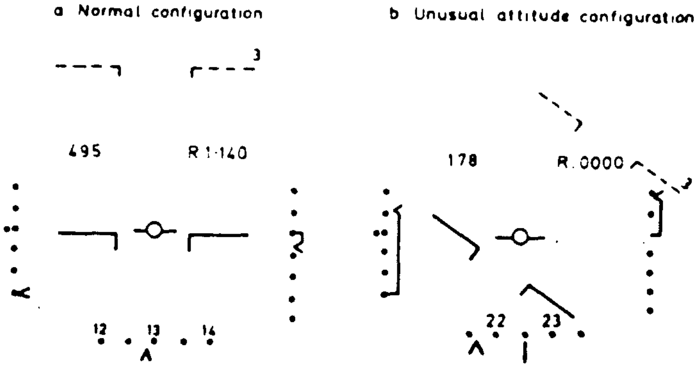


Fig. 7 HUD Symbology with Global Differences between Normal and Unusual Attitudes

IMPROVED SYMBOLOGY

Orientation in-flight should be based as far as possible on terrestrial skills. Like AIs, HUD symbology is probably an inefficient and inappropriate source of information for maintaining visual orientation, compared with a successful, and as yet hypothetical, ambient display. But again, like AIs, HUDs provide precision information for manoeuvres requiring highly resolved pitch and bank angle control, outside the capability of ambient mode processing. Also, they continue to provide pitch and roll information at high pitch angles when the natural horizon is outside the field-of-view, a situation frequently experienced during combat and emergency manoeuvres and when recovering from unusual attitudes. Wide field-of-view displays such as diffractive optics, sensor combiner HUDs (30° x 18° IFOV), panoramic displays and visually-coupled head-mounted systems should offer better opportunities for stimulating ambient mode processing with sensor-derived and computer generated imagery. A combination of focal and ambient information for future computer graphics imagery (CGI) systems has been suggested by Jauer and Quinn (1982). In this approach, dynamic, peripheral, panoramic "natural" terrain cues and artificial sky texture are integrated with central pitch and bank angle symbology for precision flight (Fig. 8). Opportunities to provide cues for ambient-mode processing in current HUDs should not be overloaded. For instance, extending the horizon line to the limits of current IFOVs would seem to be justified, if only for reasons of improved pitch-bank angle scaling, without consideration of its adequacy as an ambient-mode stimulus. Notwithstanding these points, it is important to emphasise that HUD symbology acts primarily as a precision stimulus for focal mode processing and, as discussed earlier, it should contain features appropriate for focal vision.

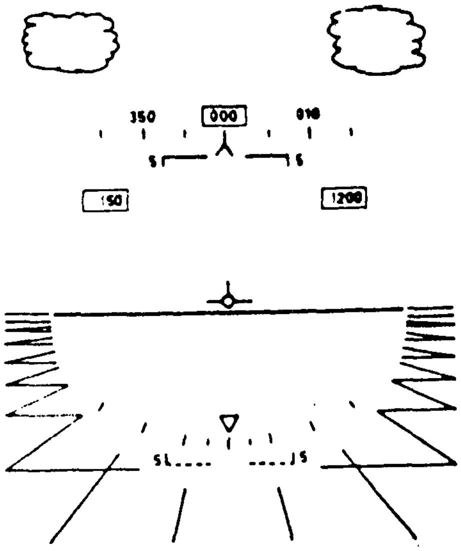


Fig. 8 HUD Pictorial Format (from JAUER and QUINN, 1982).

An improved design for a HUD pitch scale is shown in Fig. 9. This design is a spatial and functional reorganisation of the cues used in MIL-STD-884 (Fig. 3) with some additional features. It is based on an analysis of tasks and information requirements and on a systematic study of the effects of design variables on unusual attitude recovery performance reported in part in TAYLOR (1984). The experimental methodology involved the presentation of candidate formats at unexpected pitch and roll attitudes. Subjects were required to make attitude recovery control movements or attitude identification responses. Response latencies provided the richest source of design guidance. Both uni-dimensional and multi-dimensional structures were included in the candidate formats to test for local/global effects and redundancy gain performance improvements.

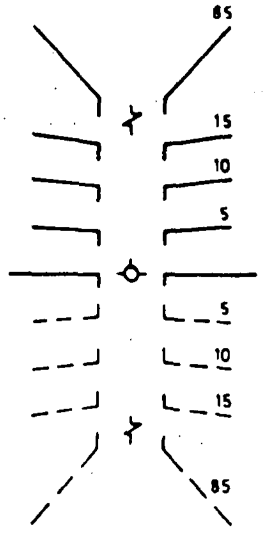


Fig. 9 Improved HUD Pitch Attitude Symbology

The rationale for the design of the improved pitch scale is as follows:

a. **Pitch Line Coding.** Positive and negative pitch angles are distinguished by continuous and broken pitch lines respectively. This provides a textural distinction which, like colour on AIs, can be recognised independent of roll orientation. Experimental evidence indicates that this coding distinction is recognised faster than differences in line shape (horizontal/sloping lines; outside/inside tags) and numeral positioning (outside adjacent/inside above), whether presented in uni-dimensional or redundant structures. At low pitch angles, the global spatial arrangement of positive and negative pitch lines about the horizon is a more effective cue to roll than nadir-pointing tags or asymmetric numerals, again comparing uni-dimensional and redundant structures. Continuous lines are used for positive pitch angles, in accordance with MIL-STD-884, because of the requirement for contrast visibility against sky backgrounds.

b. **Pitch scale numerals.** Asymmetric pitch scale numerals are provided for polar and global cues to roll inversion at high pitch angles. The global asymmetric cue is recognised faster than the orientation of individual numerals and nadir-pointing tags, whether in uni-dimensional or redundant structures. Vertical and lateral asymmetry combine as integral dimensions to produce a redundancy gain performance improvement. The numerals are located above the pitch line in accordance with normal writing practice and the principle of dominant detail on top. They are located on the right of the pitch scale, in the right visual field during normal flight, to map directly on the left hemisphere of the brain responsible for verbal processing. Negative signs are non-integral redundant cues with pitch line coding. They are omitted to reduce unnecessary clutter and obscuration.

c. **Horizon-sloping pitch lines.** Inclination of the pitch lines provides a global chevron cue to the direction of the nearest horizon. This coding of horizon information is recognised faster than horizon-pointing tags and nadir-pointing tags. The orientation to the nearest horizon of nadir-pointing tags is contingent on pitch angle. Inclination is varied with pitch angle, say with 0.5^o inclination for 1^o pitch, giving a maximum 45^o inclination at the zenith and nadir, furthest from the horizon. This chevron coding provides an analog cue for judging pitch angle, pitch rate, direct of pitch change and horizon proximity, and it is recognisible at high rates of pitch and roll, unlike the pitch numerals. Experimental evidence indicates that the inclination of the pitch bars does not interfere with roll recovery performance. Roll orientation judgements can be based on the axis of symmetry of the pitch scale, which is coincident with the polar axis and axis of balance, and on other main line axes through the numerals and the ends of the pitch bars.

d. **Pitch-bar tags.** The tags are oriented towards the horizon at the inner pitch line extremities on both positive and negative pitch lines. Experimental evidence shows that this arrangement provides a redundant coding of horizon information which is recognised faster and gives better roll recovery performance than pitch lines without tags, pitch lines with tags on the outer extremities, and pitch lines with tags oriented away from the horizon. In the recommended arrangement, the angle between the pitch lines and the tags increases with the reducing pitch angle, becoming more salient approaching the horizon. At high pitch angles, the tags combine in an integral structure with the horizon-pointing pitch lines to emphasise the chevron cue to the direction of the horizon. At less critical low pitch angles, where the inclination of the pitch bars has lower saliency, the tags provide a more distinctive separate redundant cue to the direction of the horizon. Located on the inner pitch line extremities, the tags enhance the main line axis between the inner pitch line extremities close to the aircraft symbol and close to the axis of symmetry. This facilitates the judgement of the roll orientation of the pitch scale.

e. **Horizon line.** The horizon line is thickened and extended to facilitate identification and to improve bank angle scaling. Nadir-pointing tags are included as polar features for roll inversion detection. Discrimination of the horizon line from positive pitch lines is achieved by the length and thickness differences, and from negative pitch lines by the line structure and orientation of the tags.

f. **Aircraft reference symbol.** The aircraft reference symbol has a tail-fin polar feature to facilitate recognition of roll inversion.

The symbology illustrated in Fig. 9 has been optimised for recovery from unusual, unexpected attitudes with only limited dynamic evaluation. Full dynamic testing will be necessary to determine the detailed physical requirements of the symbols such as the length, spacing and inclination of pitch lines with different pitch scale gearing. Some guidance on the structure of the negative pitch lines could be obtained from consideration of the optimum spatial frequency for contrast sensitivity (GINSBERG, 1981). In view of the substantial evidence for the display frequency-separation principle from electro-mechanical attitude indicators, serious consideration should be given to providing restricted control-compatible movement of the aircraft symbol.

POSTSCRIPT

Another approach not incompatible with the foregoing, would be to use computer generated pictorial command symbols for unusual attitude recovery. HOOVER, SHELLEY, CRONAUER and FILARSKY (1985) report the successful flight testing of an integrated Command Flight Path Display or CFPD. Altitude, direction and speed commands are presented in the form of an electronically generated, real-world flight path and a three-dimensional aircraft command velocity indicator (Fig. 10). This study confirmed that for pilots with differing degrees of experience, compared with F/A 18 symbology, the integration of real world visual cues in the CFPD required no learning or mental integration and eliminated disorientation. The authors make the important point that information from the CFPD is acquired through differentiation rather than integration.

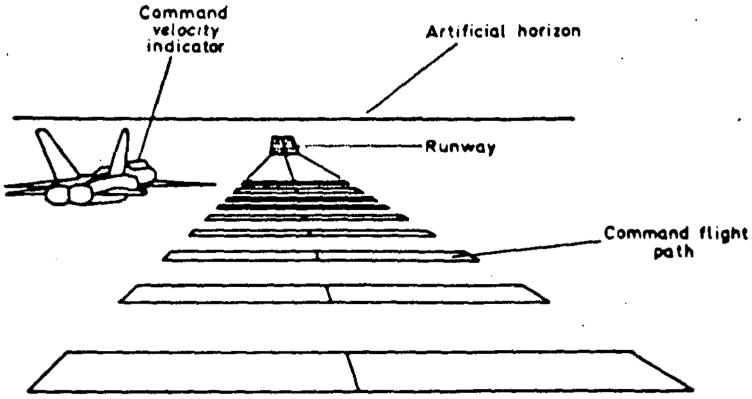


Fig. 10 Command Flght Path Display
(from HOOVER et al 1985)

By the same token, a three-dimensional Aircraft Command Attitude or "Follow-Me" Indicator, such as that illustrated in Fig. 11, would provide an immediately comprehensible cue to follow and recover from unusual attitudes.

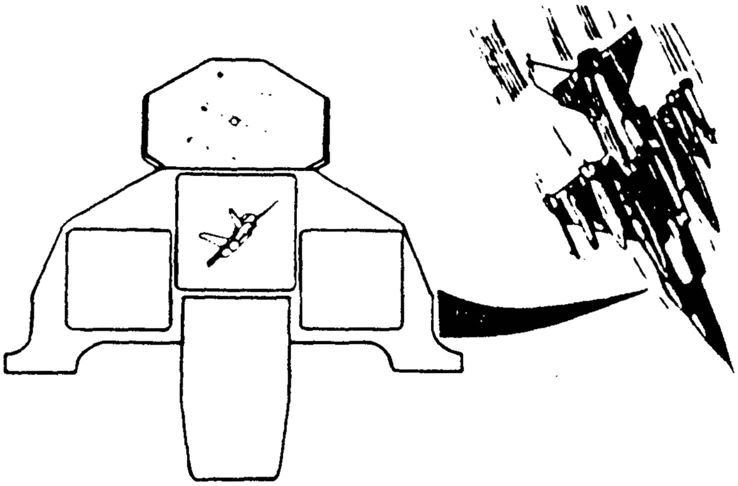


Fig. 11 HUD and Command Attitude Indicator

Ultimately the most important test of a display format is the quality of the cognition or awareness communicated about situations internal and external to the aircraft. We know that attitude awareness from AIs or HUDs is influenced by the perception of figure-ground relationships. These perceptions may be inappropriately moving-earth referenced and hence disorientated, or moving-aircraft referenced, and hence correctly orientated, corresponding to inside-out or outside-in perceptions of the outside world. HUD formats are highly abstract, symbolic representations. The quality of these representations should be judged by the extent to which they facilitate the development of situation awareness, as illustrated in Fig. 12. Improvements can and should be made to symbology. However, pictorial formats, such as the CFPD, are probably the way ahead because they offer more direct links between representation, perception and cognition than abstract, symbolic codes.

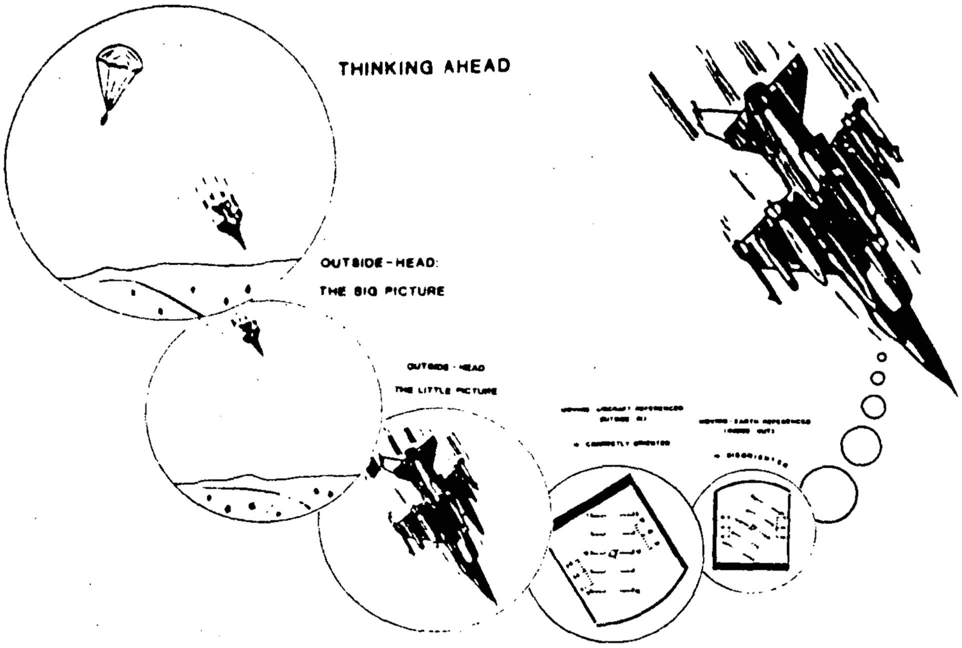


Fig. 12 Levels of Situation Awareness from Aircraft Visual Displays

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AIRCRAFT ATTITUDE AWARENESS FROM THE US NAVY PERSPECTIVE

Mr. Fredrick Hoerner
SY 70, Naval Air Test Center
Patuxent River, MD

BIOGRAPHY

- USNA '56, B.S. Electrical Engineering
- Naval Aviator '57 (Fighters)
- U.S. Naval Test Pilot School '61
- Flight Test HUD F-11, F-8, A-6 ('61-'65)
- Vietnam '66-'68, 368 Missions NVN, MIG-19 '67 (with a gun)
- Chief Test Pilot Sperry Rand
- Technical Specialist for Advanced Aircrew Displays Naval Air Test Center
- Created Display Evaluation Flight Test (DEFT)
- Chairman, Advanced Aircrew Display Symposium
- Chairman, Society of Experimental Test Pilots
- 14,000 Flight Hours, over 800 Carrier Traps.

My spot probably should have followed the A-7 or MacAir presentations.

Regarding head-up displays (HUDs), I flight tested the F-11 and F-8 and worked for Sperry Rand, who flew the first HUD in 1950. HUDs are better for VFR than IFR. One good experience is to fly around for hours on the HUD then suddenly lose the HUD and be forced to go heads down to get all the information it provides you--it's a great VFR instrument.

There is a transfer function from simulators to the real world which we evaluated in a variable stability aircraft at Calspan. The aircraft also had a variable display capability, and we found by changing the formats of displays, their size, shape, and especially dynamics, we could induce changes in the aircraft's handling qualities response without changing the flight control system. Purists don't like to hear that.

Regarding displays, we need to develop performance evaluation of displays. Everyone has an opinion about them, and there is considerable interest in displays.

Secondary task loading may be a good parameter. Studies by the British showed that when you're beginning to get task-overloaded, one of the first things you do is stop talking. Speech is one of the first channels to go when you get real busy. The pilots would say--"we're getting busy, getting overloaded." You'd say, "Describe for me what's happening." And the pilot would just clam up.

In the early days of the F-18, the Canadians and Australians were concerned about us bashing aircraft, comparable to the F-16 experience--not that it was bad, but it simply preceded the F-18 experience by a few years. They prompted us to examine the situational awareness problem and also determine whether we should be concerned.

We examined the F-18 mishaps at NAS Patuxent River. The first loss was a night GCA, no apparent problems with the aircraft; loss of consciousness was certainly a consideration.

- We had the Canadian ACM mishap.
- We had another night FCLP landing.
- More recently, we had the Catalina Island mishap, which I'd like to discuss in more detail--worth repeating because of the MFDs and multimode displays.

The F-18 has MFDs and a moving map display. At night, after you've done your navigating and are shooting the approach, you don't want your moving map display. Its reflections cause the "Star Wars" Effect; it's too bright and too distracting. The briefed procedure is to turn off the moving map and replace it with the HSI. What is an HSI? It's just a TACAN rose with DME. He had the wrong TACAN tuned in. He shot the approach perfectly, to the wrong TACAN, and hit a mountain. Had he had the map display on, he'd have seen the wrong island coming into view. What's scary is that the aircraft's sensors knew where it was but couldn't or didn't tell the pilot. You decide where the problem lies.

Anyway, we were having accidents. They seemed to be Controlled Flight into Terrain (CFIT), loss of consciousness, or loss of situational awareness, I think. And there seem to be two kinds of situational awareness: One is vestibular vertigo; the "upset" where you need to grab the aircraft right away. And the other is navigational awareness, a lot scarier, because you think you're doing everything okay. It can be a navigational error, and by the way, regarding navigation over water, I really liked those comments about flying over water--especially single engine. It's only recently we've gotten two engines in aircraft.

When you're shooting a Case Two approach to the carrier, you're supposed to break off and arrest your rate of descent; if you're working on getting the new inbound bearing to the carrier (carriers don't like to remain on one inbound bearing very long), the CCA is constantly giving you new track updates; so while you're working on track, you bust your altitude. And you're very comfortable doing it. I've done that; I've done that and I've been lost. I've had vertigo; I was glad the first time I got vertigo because I'd been briefed on it and now I knew what it was, having that identification process.

Being lost: How long before you realize you're really lost? How long does it take to say to yourself, "Self, you're lost," admit it, and get on with the program. Same thing with navigational errors. How is the aircraft able to help you?

How do we do that with the F-18 and where do we go from here with the F-18 and what was involved? Well, with me it's been from tactical maneuvering, and in those situations, you over-stress yourself or the aircraft and get yourself so involved with a kill that you lose all perspective. And by the way, the reason I used guns to kill the MIG-19 was that one missile was leaking fluid and wouldn't fire, and I fired the other way out of the envelope. I was pulling so many G's it couldn't possibly track, and I was forced to use guns. So you really get involved, and let me tell you, when you've got a silver star in your sights, your G-tolerance just goes up astronomically.

Target fixation, low level navigation--you know the only difference between a good 10° strafe and an impact is only a very, very few seconds; but how do you determine those differences?

And non-tactical maneuvering: We're going to hear some words about GPWS, I'm sorry, you are. And these are typical situations we have; just normal navigational approaches, etc.

What's the pilot got to establish Situational Awareness (SA)? You're not going to hear much new, but I'm going to suggest a couple of things though. He's got the usual, normal outside references and canopy rails. Remember going through instrument training? One peek was worth a thousand scans. You bet. And how easy it was on a sunny day with the continual shadows? No matter where the hood was, at least you had roll rate information. But also you're getting some SA from displays and instruments, so it's getting fairly complex here.

If I gave my tutorial on cockpit evolution, we've got performance data, health data; also now a lot of sensor data, which takes up prime real estate; and takes much of your time as well. Seat-of-the-pants, aural cues; can be other systems: getting the barometric altitude to talk to you. In the F-4 it was the GIB who told you when to start your level off. Not a bad deal except the GIB costs about 2500 lbs of total airframe weight. That's a consideration for our next generation aircraft. ECS? Nobody's been able to quiet the ECS yet.

Attitude of the aircraft while you're maneuvering along. In the Navy, the primary attitude reference, we console ourselves that it's the head-up display. An interesting difference emerged when that first happened. In the late '60's, the A-7E's came along: the older guys took their night cat shots head down, the new guys head up, and the performance was quite markedly different, because all you have head down is attitude. You don't have velocity vector. You can't tell what the aircraft is doing.

Flight Control System. Okay, what does the aircraft know? We're talking about the HUD, but what's the airframe know? It's got a flight control system that can tell you the G available to it. And, by the way, if you're going to limit the G, remember some of these situations we've heard about. Col Kehoe needed every G that was ever built into that airframe to avoid hitting the ground, which has a P_K of one.

The radar altimeter can really sense where the world is in cases where the surface is flat. Air Data Computer--the INS, velocity vector, energy management, radar--all the data and these sensors tell the aircraft where it is. We're suppressing side lobes now on the radar--would help SA; trouble is, you've got your headlights on which you don't want in certain hostile areas when they're looking for you. But that's what the aircraft knows. We need an information transfer, easily and readily interpreted by the pilot.

So what do we conclude about the F-18? FCS provides minimal feedback in auto. Neutral speed stability is getting to be more of a problem. Conclusion is it's better for combat maneuvering, but in other modes, e.g., ingress, certainly navigation, it's very tiring to fly X-C with a neutrally stable aircraft. If we could have a mode selectable FCS, looks like it might improve things.

Pitch attitude doesn't change much in the F-18, not with auto flaps. The attitude's the same the whole time. So now you have a pitch situation sort of like neutral pitch stability, such that the aircraft holds the same attitude to the horizon all the time.

The HUD is not adequate for quick unusual attitude recognition, period. We do have trouble with digital vs analog, and I'll be quoted from that if you like. We can't pick up trends from the digital displays and we're working software solutions to that now.

We said a lot of negative things about HUDs but let's say some good things about 'em. Accuracy: You've got one milliradian accuracy with the HUD--can't fly more accurately than that. Look at the comparisons on the Space Shuttle. All performance data: speed and dive angle was much more accurate with the HUD than before it. Compare climbout pitch on the Concorde using the ADI; their accuracy is at best one degree. The HUD is 50-60 times more accurate.

Aural cues: The engine/ECS mask all cues. McDonnell-Douglas Aircraft Corporation is proposing an aural system to tell you where the aircraft is in terms of airspeed. This is reminiscent of early experiences with the Fokker

D-8--which had the first fully cantilevered wing--no wires; and pilots couldn't tell how fast they were going without that noise feedback. Not too dissimilar.

The other displays: You can put attitude on the radar, but when target searching on it, you really get busy. When you go to radar expanded mode, of course, it's not one to one--you can get mesmerized. Our concern was not near misses but that some pilots misjudged their airspeed by over 300 kts.

FLIR, of course, is extremely disorienting. The map is good for navigational SA (when it's on). So that's obviously a problem.

The fixes this particular group came up with:

a. Improve Displays

b. Wider FOV HUD - with idea that falls into the peripheral vision display.

c. Peripheral Vision Display - not wider, just broader.

d. Analog vs digital - we're working on that.

e. Neutral speed stability - Do we need it? In certain modes, probably not.

f. Potential for a GPWS in the F-18 mission computer. If we can't come up with solutions, and by the way, I don't hear any, then maybe we've got a bandaid by giving him a warning that it's coming. Obviously, commercial aircraft have benefitted greatly from this approach. Greatly. There are documented saves in the military, too. I certainly don't like another voice or bell (warning) or the added weight or complexity to the airplane. But what's the option? How many F-16's have you lost now? How many F-18's have we lost? What do they cost? $32 million a copy. We can't afford to do that. So we said let's not degrade anything, let's get on with the program. That was what came out of that.

g. There was concern about the HUD: the HUD is not suitable for quick, snap-shot attitude interpretation, i.e. quick look at nose high attitude. Most participants disliked the digital format of the HUD. Pilots had to read and interpret individual numbers rather than getting cues via peripheral vision. Pilot work load was, of course, a factor.

h. Fixes to the displays - HUD and head down to make for rapid unequivocal interpretation, designed to be read even by the peripheral visual fields.

How much money is available for hardware fixes to these kinds of aircraft today? Three months from now, how much action do you think will have been taken? One year ago, the Secretary of Defense sponsored a safety meeting here at Wright-Patterson, seeking for answers to how we could stop bashing aircraft. I've not seen one piece of correspondence from his office helping us on some of the things we've recommended. How much money do we have for hardware? I don't know that there are any hardware fixes available except a wider FOV.

Software? Yes, we've got some pretty good ideas floating around here, and I'd like to see 'em tested in up and away flight after being validated and scrubbed in simulation. Both the Air Force and US Navy have some money to study Dr. Taylor's HUD ideas and some of the better ideas out there in the field to help us. That program will have performance criteria versus preference, which is unfortunately what we've done over the years. I'm getting tired of seeing these airplanes going in the way they are.

We took that program out to Lemoore, to the F-18 RAG and their attitude was, "if they can't hack it, they deserve to die." That's cavalier at the bar, but we just can't afford it, whether they like it or not.

One final thought: Why not a ground proximity algorithm that's wired into the FCS so that the aircraft resists crashing? I submit to you, what's the option? How many F-16's would that have saved?

QUESTION AND ANSWER

Fred Hoerner: I'm open for questions. Yes sir.

Q: Dr. William Richardson. I tend to believe like you, some type of, let's call it a cushion, that enables the aircraft, which has all of the information on a diagram, about it's status and which is not presumably confused by the vestibular sensations due to the illusions that we talked about yesterday. That would be if the pilot would turn the problem over to the aircraftto get out of the problem, in all probability, the aircraft could get out of the problem without the errors that we've seen. So maybe that's a viable solution and maybe it could be implemented in any aircraft that has an autopilot system.

FH: I think somebody used it as a selectable switch and would say, "Do that." Well I'm going just one step beyond that and say, when the aircraft's in trouble, and some of you recall the Harrier accident at Pax River. We were scheduled for a rocket run on a target and it's an extremely heavy instrumented range, and we hit the water. After the fact, we were able to go back through all of the data and show that when he fired the rocket, he was dead. Bottom line is the vehicle performance, everything was on board and knew this, but that was not transmitted to him. What I'm submitting is that if you've looked from the system out and from the pilot in, we've got to fuse that; and if there's still confusion, i.e., there's that navigation situational awareness, then let the smarter system take over.

Q: Dr. William Richardson. It's a good application for what we call artificial intellignece.

FH: Absolutely. It's scary, you know when you talk this kind of stuff to ALPA, you really get a strong head-shaking.

SOMEONE INTERRUPTS and says, I like what Gene Adam said about artificial intelligence, along with it comes artificial insanity.

FH: Or would you let your daughter marry one. Yes sir!

Q: Dr. Jerrold Gard. At least one real objection (remainder inaudible).

FH: We can't afford the option, Jerry. The option (SOMEONE INTERRUPTED AGAIN). Yes, but I'm suggesting in these extreme cases, and what I'm hearing, I don't hear a clear solution for situational awareness, but I do see that the airplane can figure it out and that the airplane has the power to take it out of there. I don't like the airplanes being taken away from me, but I'm suggesting that what is the option just from a material acquisition standpoint? Yes sir!

Q: At least one major seat manufacturer for years has been advocating what you're saying. How are you gonna overcome the pilots' attitude toward what they perceive as a partial loss of control of the situation, i.e., punching out when due to the laws of physics, you'll die if you wait any longer? How are you going to overcome that? That's the big one.

FH: I honestly can't--this is really tough. What can we afford in terms of aircraft losses due to a system that did, in fact, level it off at 4 or 5 g's at 1500 ft AGL, and just holds it there until the guy reawakens. Yes sir!

Q: What would be the parameter that it recovered to, as I can see a lot of controversy coming; in other words, if you state that the airplane is always going to recover at 1500 foot, well that's not very tactical for it to do that. In other words, I can just forsee certain things where the airplane would say, "Hey, this is uncontrollable", or the pilot may want to go down to 200 feet, he may want to do a split S and recover at 200 feet; he may be attacking and have options that he wants to exercise.

FH: I understand. All I'm suggesting is that we can't afford the losses that we're presently incurring.

Q: There's a point where the pilot gets paid if we had gone down to training relative to enough purposes to determine training, but the next step from what you're saying is well, let's program the airplane to take off by itself and program it to do all the things by itself as well as have communication. But, again I feel the pilot has some responsibility to avoid the airplane flying into the ground.

Dr. McNaughton: If I could just have a moment, we're going to talk about this in the morning. We've got a full hour devoted to automatic recovery systems.

FH: I knew that this would get into that; that's really tough, but I don't see a clearcut solution to loss of situational awareness and losing airplanes in let's just say the next ten years. From the kinds of airplanes that we're buying and the kinds that we're going to be selling, F-16's, F-18's, for a long time.

Q: I guess I miss the point of the moving map scenario.

A: The moving map caused him to turn off the HSI, which would have given him the situational awareness that he was closing on Catalina. He really would have seen the wrong terminals, it was the wrong island, it doesn't look on the map at all like San Clemente which was what he was heading for. But the information was there and would have been presented to him--it would have been as it moved into the view, he would have seen Santa Catalina, Avalon Harbor, all this good stuff, and said, "whoa". He had another cue available to him to show that he had the wrong TACAN. Thank you.

ROLE OF THE STANDBY ATTITUDE INDICATOR

Mr. Richard Geiselhart
ASD/ENECH
WPAFB, Ohio

Biography

Mr. Gieselhart was graduated from Brown University in 1953 with A.B. degree and received his M.S. in Experimental Psychology from the University of Pittsburg in 1959. He served three years in the U.S. Army in the interim. He joined the Behavioral Sciences Laboratory, at that time part of U.S.A.F. Aeromedical Research Laboratories. While at AMRL he conducted research on operator training and control systems for spacecraft. He then conducted several field research projects with Air Training Command on methods for improving UPT (Undergraduate Pilot Training). In 1966 Mr. Geiselhart transferred to ASD as part of System Engineering Group (later to become Deputy for Engineering) and worked on the C-5 and U.S. /Federal Republic of Germany Visitor Program. On the C-5A he developed a program to improve the readability of technical manuals. Later in 1966 Geiselhart founded ASD's Crew STation Design Facility which he has since developed into a 25 million dollar facility.

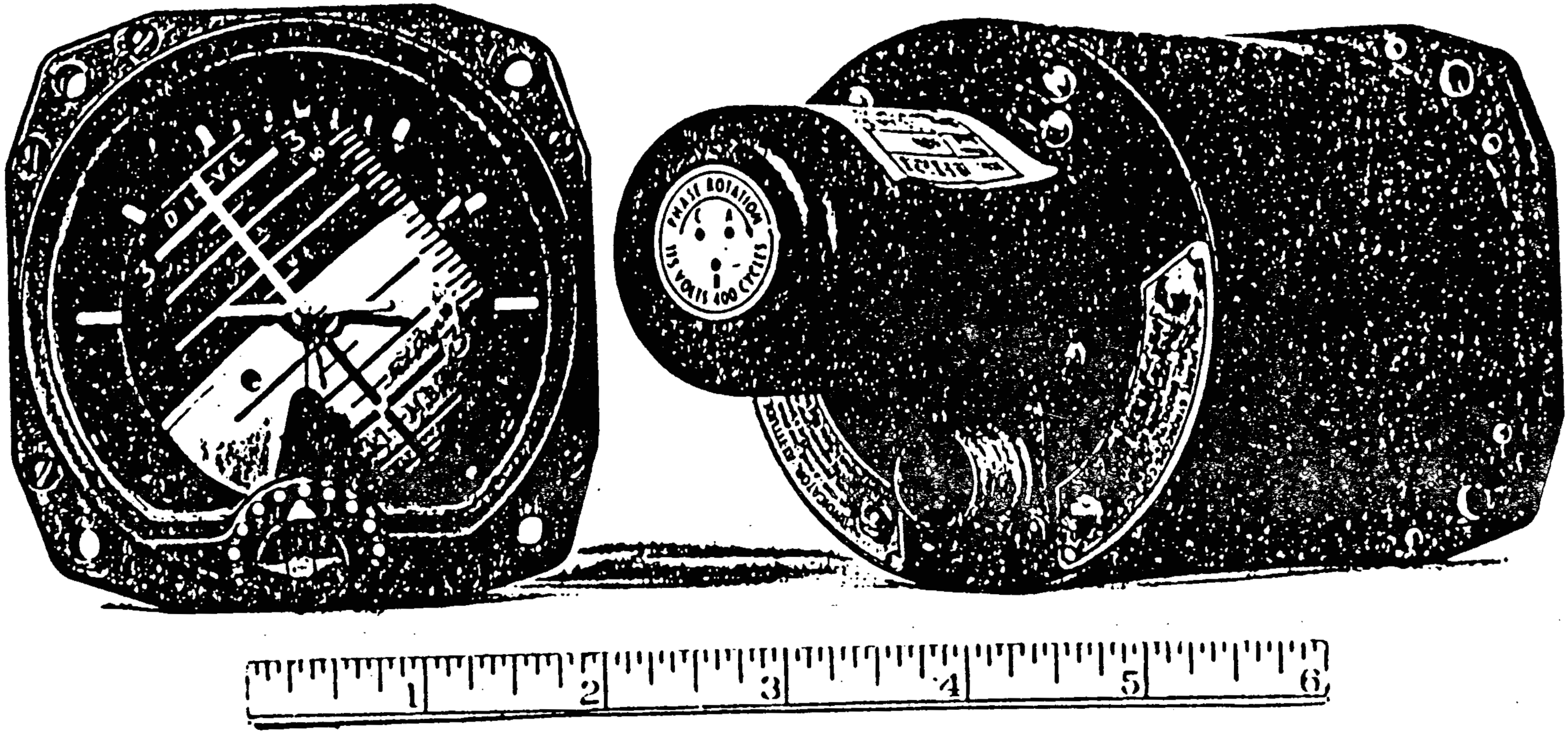
Under Mr. Geiselhart's superior technical direction, the facility has successfully tested, modified, and evaluated program efforts including the F-16, LANTIRN, C-5, B-1, Remotely Piloted Vehicle (RPV), and Joint Tactical Information Distribution System (JTIDS) to name a few. From its inception until the present, under Mr. Geiselhart's tutelage the CSDF has conducted over 100 short term and long term studies for ASD. Of these, over 25 have been published as technical reports whose topics range from workload, wake vorticies, cockpit design, to ground collision avoidance, and situation awareness.

ROLE OF THE STANDBY ATTITUDE INDICATOR

That's a rather exciting introduction for a rather dull topic: Standby Attitude Indicators. I don't think it turns many people on: however, we'll get moving with it. First of all, I'm going to give you a historical perspective and a background. I may plow over some of the ground that Pete Lovering did this morning, but I'm only going to do it briefly, just to set the scenario for why you need standby indicators. Then I'm going to talk a little bit about the characteristics of standby indicators, where we put them in cockpits (and I sometimes wonder why we put them where we do) and then I'm going to talk about some related issues: how the HUD plays a part here and then I'll briefly take a look at what I think may be coming in the future.

I'll be flipping back and forth on these. The first attitude indicators were vacuum run, built by a company just up the road here in Cleveland, Ohio, called Jack and Heintz. It was interesting researching this problem; finding that we still had pictures of a lot of these things. Then in '45 we decided to go electric gyros. The faces remained the same. The reason I am getting into what powers them is that is the reason why we have standby indicators. Now the J-3 sphere (Figure 1) appeared and it presented a human factors problem. This was, incidentally, Stan Roscoe's first job as a graduate student, consulting here. You will notice that we have got the dive, black on top and the climb, white and on the bottom. And that was the beginning of a long history of inside out versus outside in, which, I guess I am not going to escape. I have about 3 more years to go until retirement and I'm sure that I'm going to have to look at that damn thing again. Then Lear came in with, what they call, their model 978. And it improved the accuracy and it really started moving into the modern era and they start using remote gyros there and it was used on almost everything from the B-36 to the RB-66, RB-47. This is kind of what that looked like (Figure 2). Then this is the Lear 978K and F and you can see the beginnings of the modern ADI right there. Then we moved into the modern era when the first standby starts showing up. This is the first time we had a standby kind of thing. The so called needle, ball, and airspeed. So if you lost power to your ADI or were getting inaccurate information you could go to this. Looking at some other advancements. Then the F-111 came up with the ARU11B and you not only had needle, ball and airspeed, you had three sixty. We only went through one generation of these. I guess the information could not be read precisely enough, I never was able to figure those out. And then of course, now we are moving into the electronic era. And our ADIs are going to start looking like this (Figure 3) and the standbys are going to present some sort of a different problem for us, I think. I'll discuss all these items.

The need for the standby indicator arose out of several considerations. One was we did have a reliability problem with our ADIs. There was quite a wide range and it was not unknown



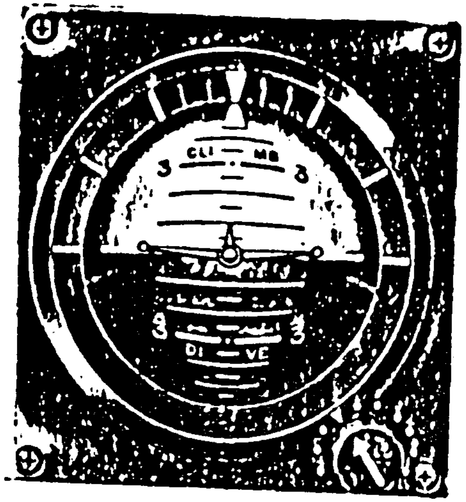
J-3 INDICATOR/ATTITUDE GYRO

SPERRY GYROSCOPE DIVISION 24 AUGUST 1948

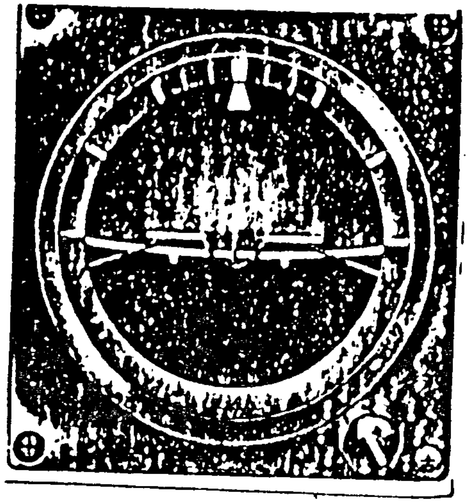
FLUORESCENT-RADIOACTIVE MARKINGS

Figure 1

VERTICAL GYRO INDICATOR SYSTEM

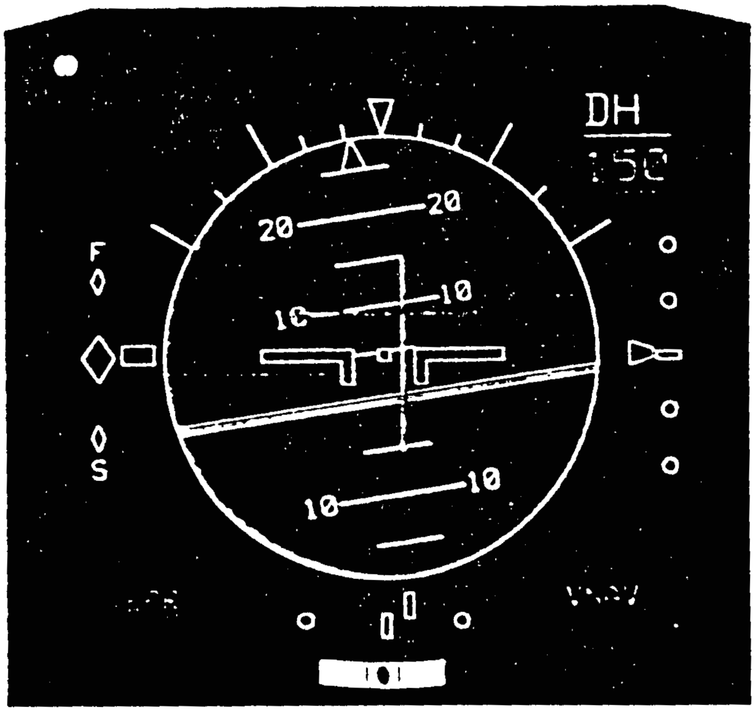


LEAR MODEL 978-K



LEAR MODEL 978-F

Figure 2



ELECTRONIC ATTITUDE DIRECTOR INDICATOR

for the operators to lose power to the main ADI. Most ADIs had warning flags for loss of power only internally to the indicator. Now, if you get into an insidious failure, where you are not getting 110 volts into that indicator, you are going down to 90 or 80 volts, you are not going to get that flag, and the information is going to be not correct. And that is sometimes hard to find. So at that time TAC and some of the other fighter communities started saying, "Maybe we need a standby or a backup or if we take a hit and we lose power to our ADI maybe we could use some kind of a backup." So the first ones to come out were what they called remote standby indicators. You had a gyro system feeding a 2 inch indicator. And I'll talk a little bit more about that when I get to the indicators. But two problems still exist when you have two attitude indicators in a airplane. One says one thing, one says another thing. Which do you believe? The tendency is to believe the big one, I think. Whatever the reason. But we have some answers for what we do about that.

And what do you do in the case of total loss of aircraft power? So even if you have got a remote standby, you are going to lose that power, too. So the the next thing that came along was the self-sustaining system which was able to run off of a battery and it also had the coast capability that allowed it to run for 9 minutes with no power in the aircraft. At least that will help you keep the aircraft straight and level and get turned for home in the right direction. It had a high acceptance in Tactical Air Command because they liked the idea that if you lost all power, you had something to recover with. Some of the disadvantages were that there was no sky pointer available, which pilots had become used to, and a shim was also required because the gyros are self-contained in the instrument and had to be sitting perpendicular in the cockpit.

Now there are two types. As I said, there is the remote type and there is also the self-contained type. The remote type has got the old MC1 gyro with the 2 inch indicator remoted, it's used in the T-38, F-105, F-111, A-7; we still use a lot of these and it has plus or minus 82 degrees pitch and unlimited roll and its got about a 3 degree to 8 degree error depending on how fast the rate during the loop. It is not very effective in high turn rates, but I would assume that when you got in that situation you would refrain from doing that sort of thing if possible. It has no cage capability. What they call fast self-erect is 10 to 15 degrees a minute, which is probably too slow for a fighter pilot. But so the model 803, and that's built by J.E.T., I think, is a self-contained standby 2 inch gyro horizon. And it's made specifically for the fighter aircraft and as I said earlier, it has a 9 minute coast time after power loss, it has a cage capability which is almost always used, recovery time is relatively slow. It's got 360 pitch and roll and it is also DC powered. These are the two indicators (Figure 4), one of each type that we are talking about. Here, and this one is used in the F-16, the A-10 and some others. As I said, this is used in

STANDBY ATTITUDE INDICATORS

REMOTE SYSTEM W/ MD-1 GYRO

SELF-CONTAINED MODEL 803

Figure 4

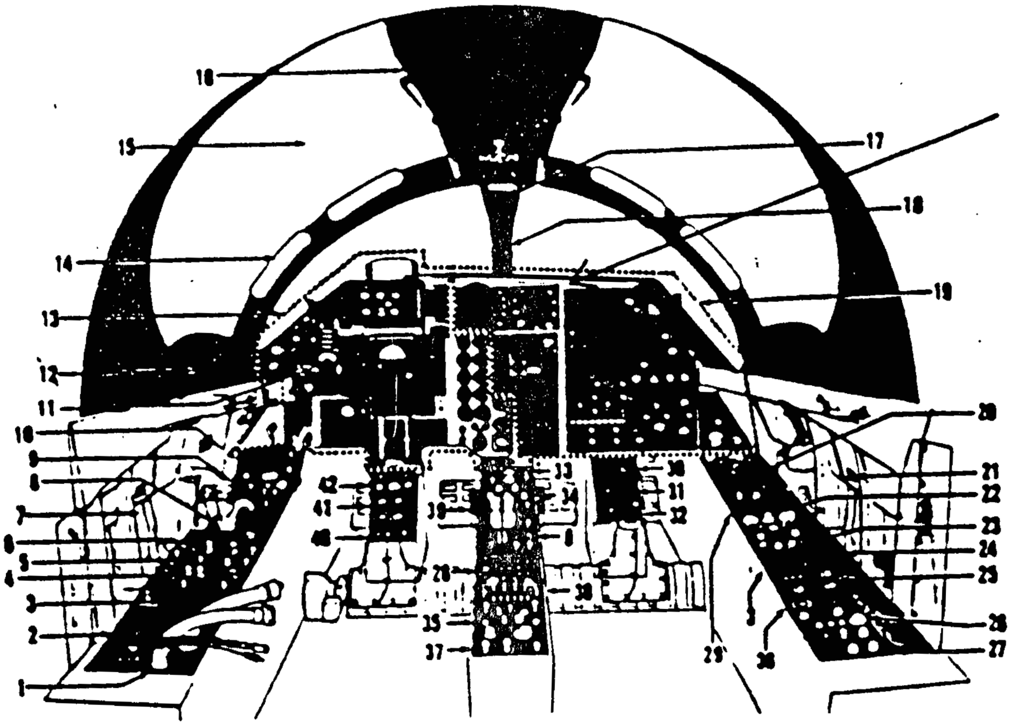
the F-111 and some other vintage fighter aircraft.

There is some fiction and fact concerning these things. I got as many of them as I could from the instrument people in researching this. Many people think that if you roll the aircraft you have to re-erect the gyro. As we said earlier, control turn rate is 3-9 degrees error. That is not the problem. Now, many pilots believe that the gimbal prevents precession errors. That is not true. That gimbal lock was put in there so that it doesn't get knocked around when it is shipped. And some pilots use a power to power shutdown. They think it will save the instruments; the vendor says that this is really unnecessary. There are provisions in the instrument for that. It will self-correct up to 7 degrees, which is time consuming, so the manual cage, as I said, is a little bit faster. They are DC powered and the gyro will tumble when it hits a stop, so you will have to re-erect it when you do a loop.

Now, I want to talk a little bit about placement, and they really jump around the cockpit in a lot of airplanes. This is where it is in the F-111 (Figure 5). Its quite low and to the right. Of course, being a side by side airplane, this does have the advantage that if for some reason the WSO (Weapons System Operator) has to take the airplane, he has the instruments close by him. But it is a little bit far for the pilot's seat, if he has to use it.

Now one thing I was not able to find is any data on how often any standby indicator has been used. As far as I could tell, I talked to a lot of pilots, no pilot that I ever talked to told me that he had occasion to use the standby ADI. Here is where she is in the A-10 (Figure 6). We got a pretty good placement in the A-10. This is the self-contained unit (Figure 6) I think this is a good spot for it. It works quite well. Now in the F-16, it is in this area right here (Figure 7). You can't see it too well in this particular picture because of the angle. We were trying to look at the data entry display (DED). So I am going to resort to a artist's schematic to show you where it is. The self-contained ADI is right under the data entry display. In the F-18, as you can see (Figure 8), this is really not a standby ADI in the true sense of the word and I am going to be talking about that in a minute. This is really a regular ADI, but because the HUD is considered the primary instrument, what formerly was a primary instrument now becomes a standby instrument. I am going to talk about that in a few minutes.

Some related issues. One of those is the triply redundant attitude information. About 15 years ago we had a rash of accidents involving insidious failures in the ADI or conflicting information. You had two ADIs in the airplane and you didn't know which one to believe. The son of the Chief of Staff, General Ryan, was killed in such an accident, and some action was taken and TAC adopted the policy of having three sources of attitude information available to the pilot in the cockpit. The



Standby
ADI
Location

Standby ADI

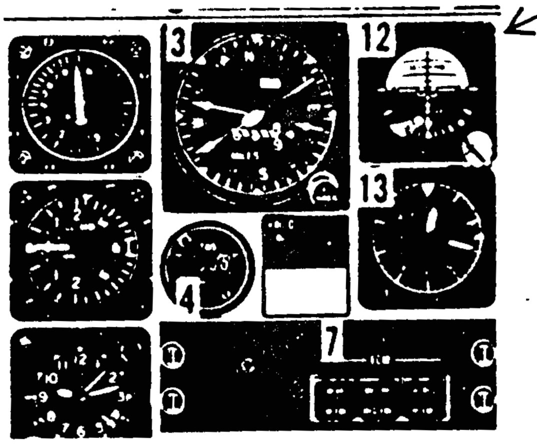


Figure--5 F-111 Cockpit Configuration and Standby ADI

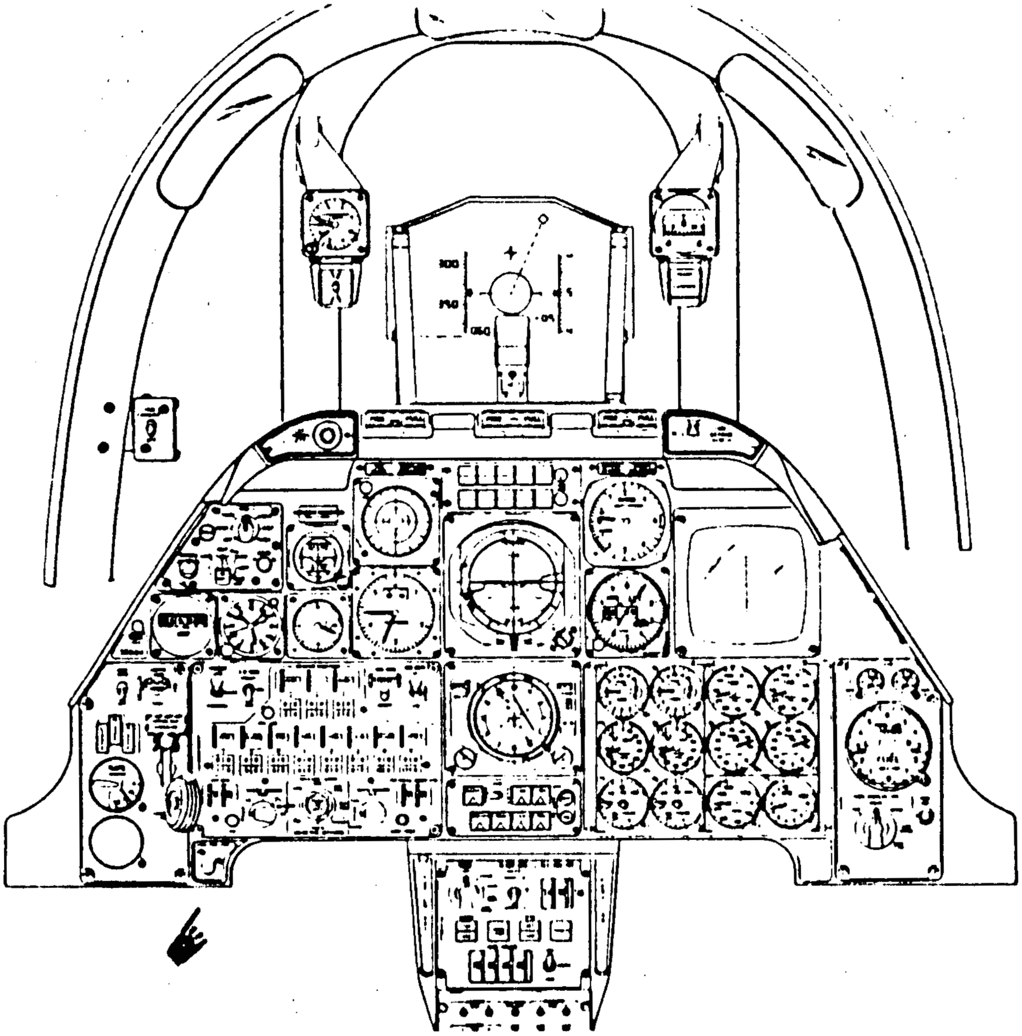


Figure--6 A-10 Cockpit Configuration

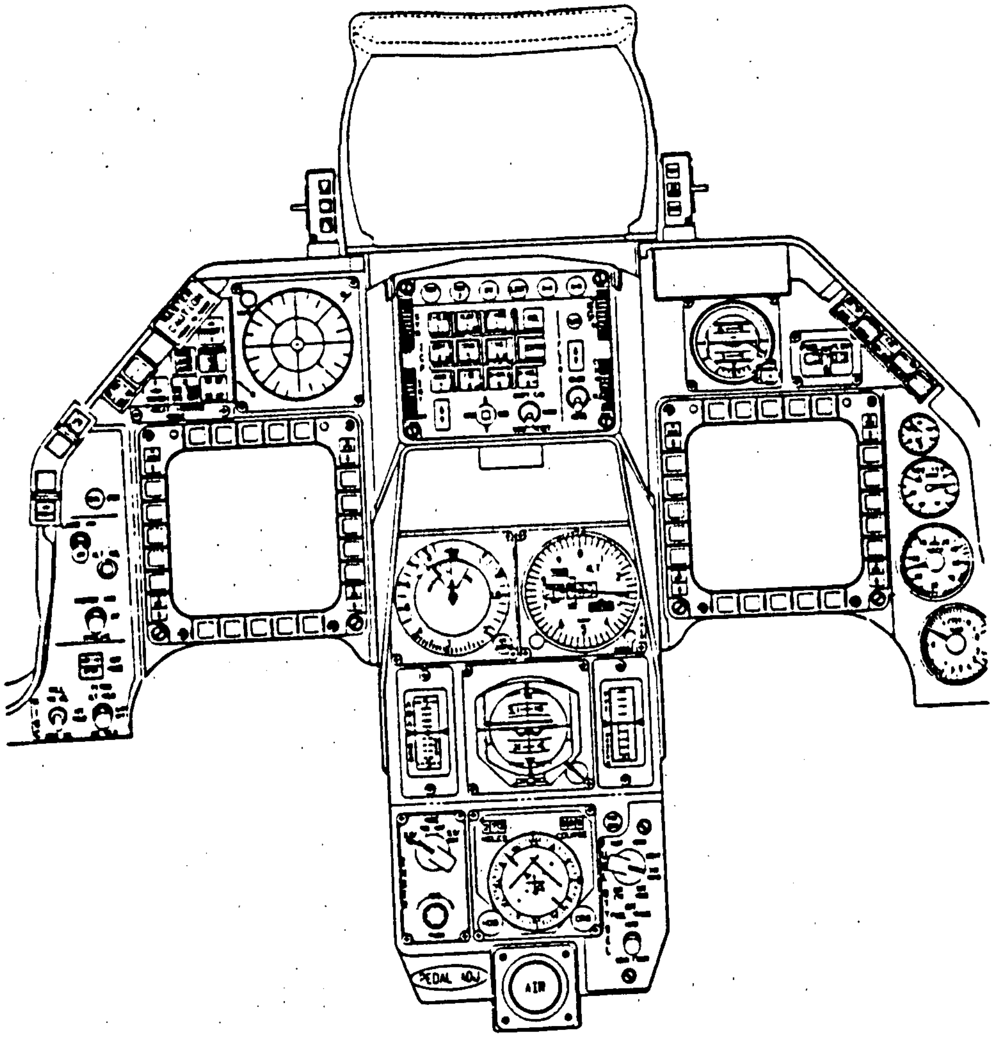


Figure--7 F-16 Cockpit Configuration

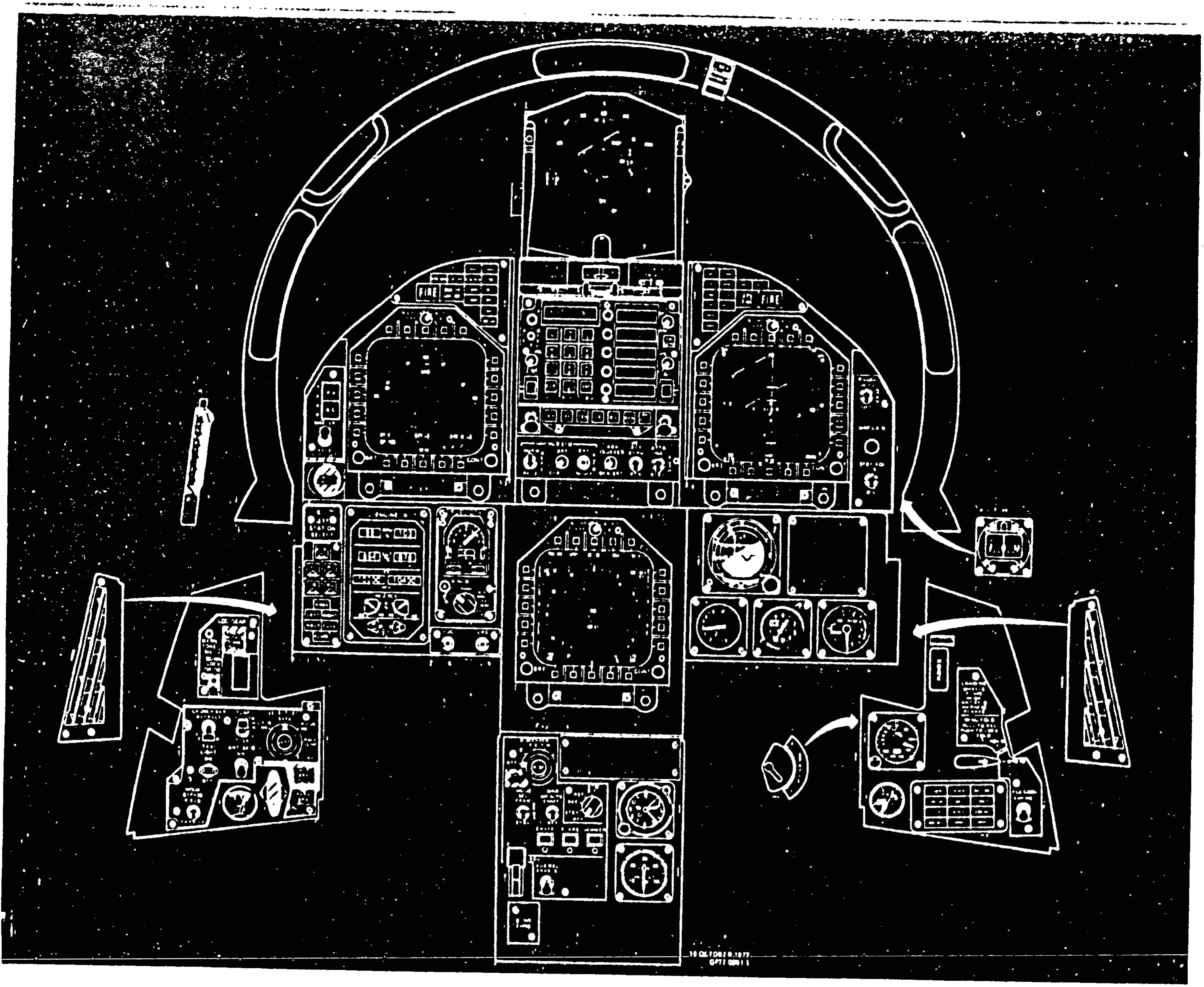


Figure 8

F-111 also put a comparative monitor in there to help make some determination which ADI was bad. They use a DC powered ARU-42. Now in the F-16, you do have redundancy but it's in the indicators only. You have three indications of attitude so if you have a failure in an attitude indicator, you have a backup. But the gyros feeding them are not triply redundant, they are doubly redundant. (Source for the ADI and HUD is the Inertial Navigation System; that for the SAI is its own gyro.)

Another subject near and dear to my heart is the lack of precise attitude information in HUDs. Now, about 6 weeks ago I attended a conference in Washington where we participated in fixing Air Force policy concerning instrument flying and head up displays. One of the things that came out of that meeting was that heads down information was a necessity if you are going to use the HUDs "as a primary instrument." That's under review right now, but that looks like that is the way it's going. Well, when you go heads down you have got another problem on some airplanes. And it's coming up and it's going to come up more often. It's the electromechanical versus the CRT display. Now in the C-17, the HUD is going to be primary. The heads down is going to be on an electronic display. And the heads down information is going to be largely a repeat of the information he sees on the HUD. I have problems seeing how, if he has problems looking through the HUD, how looking down at the same information is going to help him. So that's something to think about. The other one is the multi function display is that also happens to be on the multi function display. Well the Air Force policy is probably going to say that it has to be immediately available. So the pilots tell me that it is a pushbutton away. But what is a pushbutton away when you have a MFD with 15 buttons down the side and you are disoriented? Are you going to hit the right switch? Are you going to be able to call that information up? That's the question we have to think about.

So what is in the future? What are we going to be doing with standby instruments? Well the glass cockpit is inherently redundant as far as the indicator side of the problem is. Where we had to worry about a failure internal to the electromechanical one, you are going to have three or four MFDs up there and you just run the data bus and you can put the attitude information anywhere you want. So the attitude source is what we must worry about having a backup for. We are going to have enough redundancy in what's feeding those multi function displays. Another thing, when we go to the all glass cockpit, or as the F-16 is called, the all-electric airplane, where you get a power loss, you lose everything, you lose the data bus, you lose everything on the airplane. So, the standby is going to become somewhere in the power source. We are going to have to use either ram air turbines, so called RAT, we use hydrazine powered APUs so it comes up very quickly so we don't lose power to the computers for very long so it doesn't lose its memory. Perhaps we are even looking at a self-contained electronic standby indicator. The guy from Jett was here, I don't know if they are working on that. And finally, since a lot of times we go to the ADI for loss of situation awareness, I was talking to one the human engineers from the Israeli Aerospace Industry and one of the things they are going to put on the LAVI, and I don't know if we are going to talk about this later, is the vertigard. This is tied into the digital flight control system; if you go into a cloud bank or feel that you may be disoriented you hit a button and the digital flight control system levels the airplane and brings it to a slightly nose up attitude. So you kind of use that as a check if you are going into a situation where you think you might get vertigo. So that is what I see possibly coming up and that pretty much covers what I have been able to research concerning standby ADIs. Any questions; I will be happy to entertain them?

Question: The Air Force generating a spec in light of the glass cockpit phenomena turn in what the old attitude source should be, for instance, the primary source is typically the inertial platform. Are they planning on

Answer: First, if there is an avionics man in the room, he is more responsible for that spec than I am. But I would imagine that we are going to have to look at something like that.

Question: The FB-111 amp is going into flight test with two INS's; primary and secondary INS and still retains the capability. . . The thing I would like to point out is that the entire TAC 111 fleet has primary INS and ADI and the standby ADI driven by a remote gyro and then had the third self-contained ADI added back there when you were talking about . . . TAC is the only ones that went with comparator, comparing primary with secondary with no third thing to vote with.

That was in the 111? Yea, okay. Thank you.

Question: The A-10 carries an INS and an A-harness. When you pull back on the A-harness it would automatically drive both the INS and the ADI.

Answer: Yes, but I think he is alluding to the glass cockpit, which neither of those are.

Rebuttal: The 86 does the same thing and it has an MFD for attitude.

THE MANEUVERING FLIGHT PATH DISPLAY CONCEPT

by
J.F. Watler, Jr.
Northrop Corporation - Advanced System Division
Pico Rivera, California

BIOGRAPHY

Frank Watler is a technical manager at the Advanced Systems Division of Northrop. Frank served two tours of duty in the Marine Corps - in the infantry in WWII, and in aviation during the Korean War period as a radar observer in all-weather fighters (the Grumman F7F Tigercat and the Douglas F3D Skyknight). He also owned and operated a Model B Navion for many years.

He attended Georgia Tech between the wars (i.e., WWII and Korea) and holds B.S. and M.S. degrees in Engineering from UCLA. In school, his areas of interest were aeronautics, electronics, control systems, applied math, and biotechnology.

In the late fifties and early sixties, while at Douglas Aircraft Co., Frank worked on the Army-Navy Instrumentation Program (ANIP) where the concepts of the "contact analog" and "flight path" displays first emerged.

He joined Northrop in 1974 and has since been responsible for developing the Controls and Displays Evaluation Model (CODEM) and the Maneuvering Flight Path Display. The former is a method for engineering the cockpit controls and displays to quantitative crew performance criteria. The latter is the subject of his presentation today.

The concept of a flight path display first emerged from the Army-Navy Instrument Program (ANIP) in 1953. The computer technology at that time, and until the ANIP was terminated in 1963, limited the flight path development to the relatively static version featured in the A6 aircraft. Northrop, independently and with Navy sponsorship, has worked since 1975 to develop a fully maneuvering version of the concept. This version, the Maneuvering Flight Path Display, is the subject of this paper.

In all aircraft, the pilot is confronted with two fundamental problems - the control of his vehicle's flight trajectory, and the operation of his system as the vehicle proceeds along that trajectory. Since all else, including the pilot's life, is dependent on proper trajectory control, let us focus our discussion on that problem.

First of all, what do we mean when we talk of vehicle trajectory control? In a gross sense, we mean control of the vehicle's flight path in four dimensions: X, Y, Z, and time. More precisely, and in terms of greater personal interest to the pilot, we mean control of the vehicle's geographic position (latitude and longitude), attitude (roll, pitch, and yaw), altitude, speed, and direction.

Now let us examine how the pilot controls his vehicle's trajectory in present day aircraft. In contact flying, the pilot maintains visual contact with the ground and sky and, referring only occasionally to his cockpit instrumentation, maneuvers with respect to the horizon and other earth-related references. In instrument flying, the pilot visualizes the trajectory he wishes to make good (in order to preserve his real world orientation), refers continuously to various parametric displays in the cockpit, correlates the cockpit display parameters to his mental image of the trajectory, and controls the parameters so as to adhere to the desired flight path. In many cases, the pilot is required to fly under conditions in which the two types of flying are alternately involved and frequent transitions between the two are necessary.

The pilot community will acknowledge that pure contact flying is the easiest, that pure instrument flying is difficult in that it entails an unbroken succession of complex cognitive tasks, and that an intermittent mixture of the two can often prove to be the most hazardous (say, when a transition to instrument flight is required following a visual, low-level, air-to-ground attack). Accordingly, a vehicle trajectory display which presents the essential control information accurately in a pictorial representation of the corresponding contact flight situation should reduce the complexity and increase the safety of flight, while simultaneously affording the same high level of control precision under all three conditions.

But how should one go about creating such a display? A re-examination of the fundamentals involved is always advisable, so let us start there. We know that five basic visual cues are involved in contact flight - internal reference, external reference, linear perspective, surface texture, and motion parallax. These cues are depicted graphically in Figure 1.

The internal reference is provided by the windscreen frame or canopy bow. The external reference is the horizon. Every pilot is aware of the importance of these two cues because they are prominently involved in his first flying lesson. The instructor demonstrates where the horizon should be relative to the windscreen frame for level flight and standard rate turns to the left and right, and the student pilot is taught to control the aircraft solely by reference to the two cues.

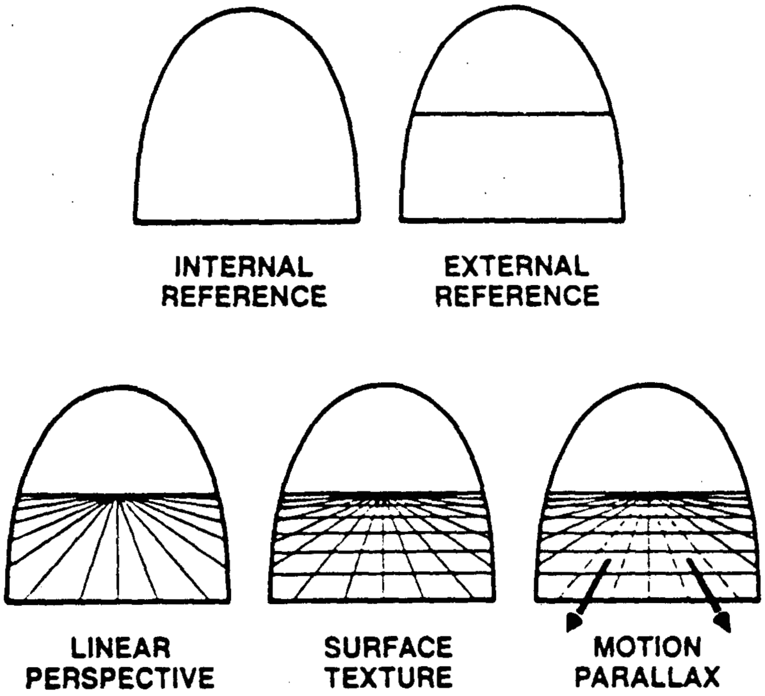


FIGURE 1. VISUAL CUES INVOLVED IN CONTACT FLIGHT

Linear perspective is the cue that enables us to judge distance. Objects of the same size appear larger or smaller as an inverse function of their distance from the observer. Surface texture enhances our judgment of distance and enables us to discriminate and identify individual objects.

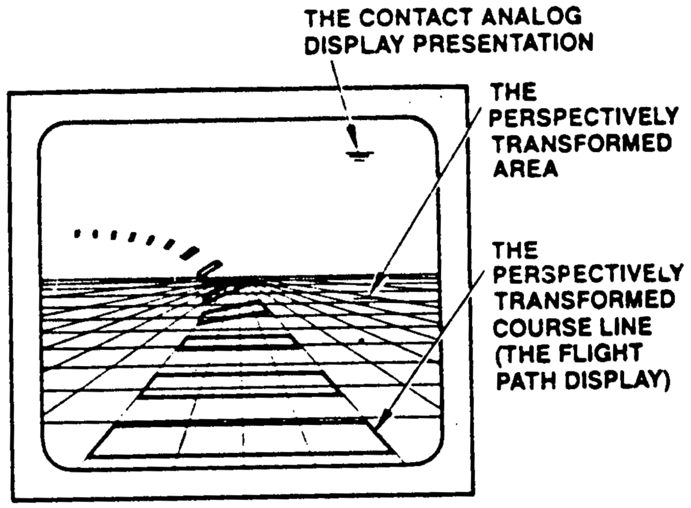
Motion parallax provides the dynamic reality involved. Simply stated, it is the motion of the ground which we perceive as a consequence of our own movement. In that perception, objects in the near field move proportionately faster than objects in the far field. For example, imagine that you are driving down a country road at night under a full moon. While it appears that you are "flying formation" with the moon (i.e., there is no movement of the moon relative to you), the trees and telephone poles on the sides of the road are moving by you rapidly.

It appears then that our trajectory display should incorporate geometrically correct representations of the five visual cues of contact flight.

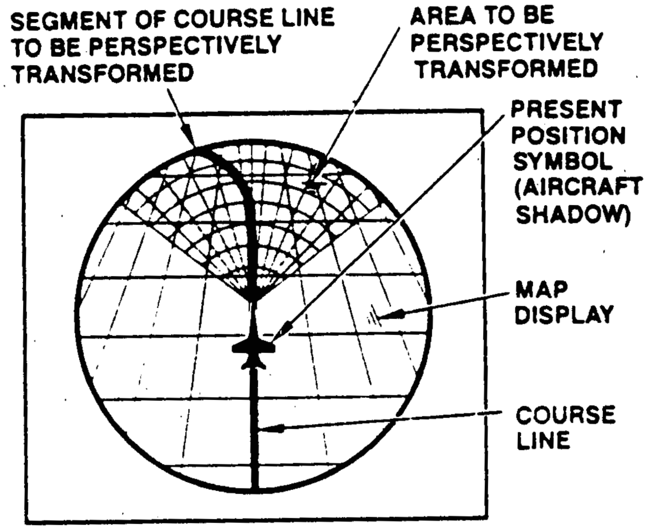
Fine! But how do we get the required trajectory information into the "contact analog" format? Again, we examine the fundamentals of the situation. The desired "highway in the sky," which we visualize in order to maintain our real world orientation during instrument flight, is capable of providing almost all of the director information elements we need - if, we were to make it visible and give it geographic fidelity (i.e., tie it to particular points on the surface of the earth). Since the "highway" is simply our planned course through earth-referenced space, we can perspectively transform that course and end up with a flight path display presentation which is inherently compatible with our "contact analog" display concept. Figure 2 portrays this transformation as it would appear on a vertical situation display (VSD).

The pilot would stay on course by flying down the center of the flight path just as though his landing gear were extended and his task were to taxi on the flight path. The elements of the flight path display are analogous to "tar strips" on a highway. Hence, these synthetic tar strips move at a rate equivalent to the prevailing groundspeed of the vehicle. The continuum of tar strips provide the command information which the pilot uses to control his attitude, altitude, and direction. A horizon line serves to provide that additional situation information needed to ensure the pilot's orientation in the real world.

We now complete the director information by adding the means for the pilot to control his speed. A real world analog velocity index, which is a computer graphics depiction of a "lead" airplane flying at the proper speed, is placed to the left of and about two landing gear heights above the flight path display. When we are flying at the proper speed, this "lead" airplane holds position on comfortable distance (equivalent to a loose cross-country formation position of about 700 feet) in front of our trail aircraft. When

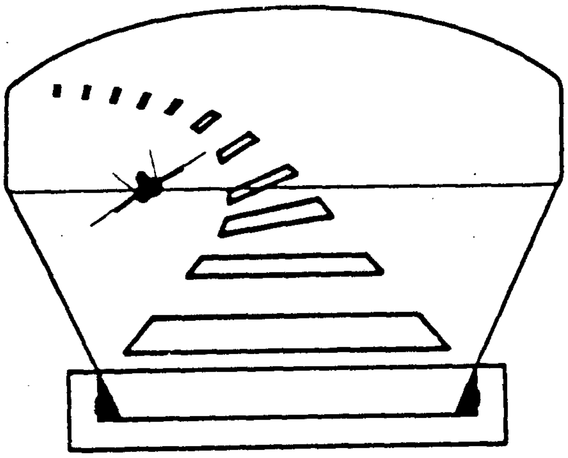


VERTICAL SITUATION DISPLAY



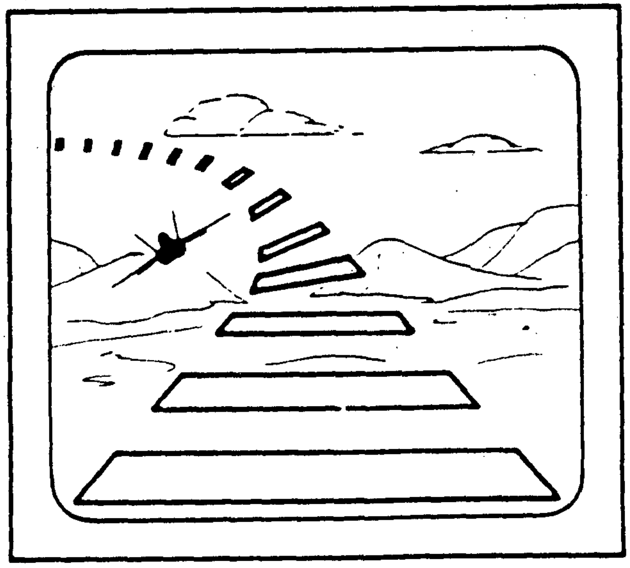
HORIZONTAL SITUATION DISPLAY

FIGURE 2. THE SOURCE OF THE FLIGHT PATH DISPLAY



HEAD-UP DISPLAY PRESENTATION IN VISUAL FLIGHT

- FLIGHT PATH DISPLAY
- VELOCITY INDEX
- HORIZON LINE



HEAD-DOWN VERTICAL SITUATION DISPLAY PRESENTATION

- FLIGHT PATH DISPLAY
- VELOCITY INDEX
- TERRAIN INFORMATION
- SKY TEXTURE

FIGURE 3. HEAD-UP AND HEAD-DOWN PRESENTATIONS OF THE MFPD

our speed is too great, we close on the lead aircraft; when we are too slow, the lead aircraft moves away from us. The addition of this velocity index gives us kinetic energy management capability, in addition to the potential energy control extent in the projected tar strips, and turns our simple flight path display into the Maneuvering Flight Path Display (MFPD). Also, the velocity index our altitude control by providing the upper limit to augment the lower limit inherent in the flight path display itself.

Figure 3 shows how the MFPD would appear on a head-up display (HUD) under visual flight conditions and on a head-down vertical situation display (VSD) of the future. The MFPD on the HUD under visual flight conditions would consist of only the flight path display, the velocity index, and the horizon line. Under instrument flight conditions, the HUD presentation would be essentially the same as that shown on the VSD. Thus, when the needed situational information is not available from the real world, it would be provided synthetically. Figure 4 is a photograph of the Northrop MFPD during landing.

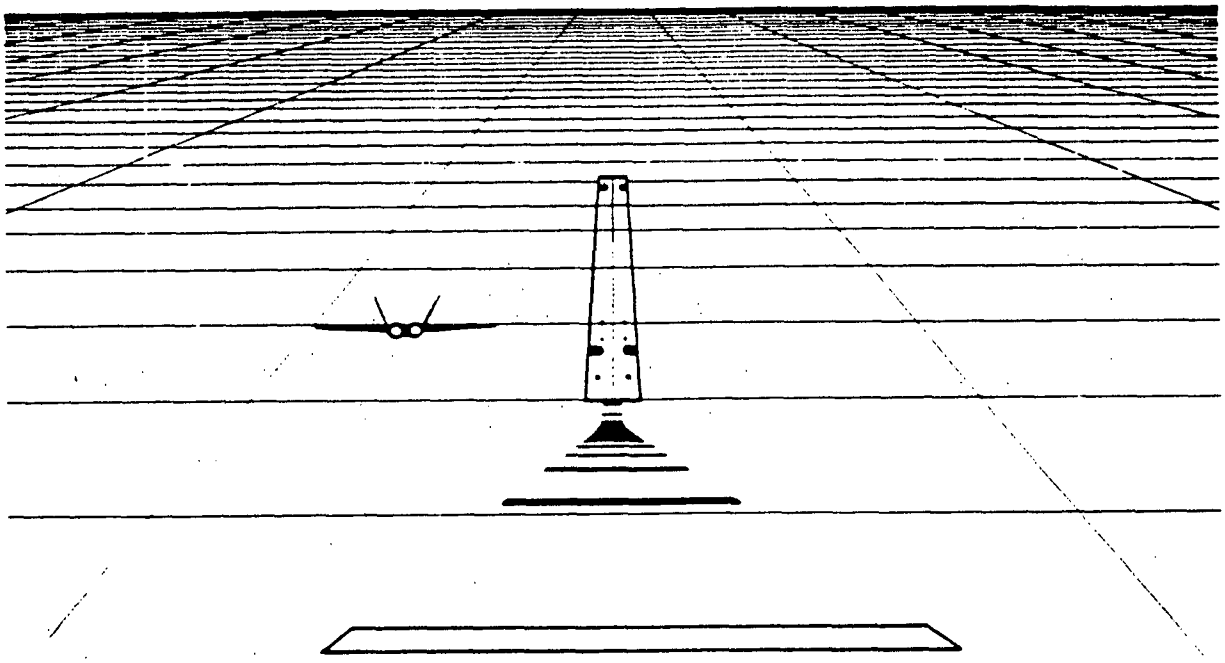


FIGURE 4. MANEUVERING FLIGHT PATH DISPLAY PHOTO

In summary, the MFPD provides all of the pilot information required for easy, safe, and precise trajectory control and it does it in a way that is operationally compatible with head-up, tactical flight. Specifically, the pilot can respond to the display with his peripheral vision in much the same way he drives his car, since the complex cognitive tasks associated with conventional instrument flight have been replaced with the simple conditioned responses associated with driving. Further, the MFPD presents the necessary command/director information in an easy-to-understand solution format which simply shows what needs to be done and how, when and where to do it. It also provides the anticipatory information the pilot needs to stay ahead of his vehicle and to execute promptly and properly the required maneuvers. The director information of the MFPD can be supported easily with compatibly formatted situation information that provides the orientation, status, and trend information the pilot requires to determine what he is doing, how well he is doing it, and whether to accept, reject, or postpone the director information being provided.

In addition to its workload reduction features, the MFPD incorporates a number of capabilities that make it operationally appealing as well. For example, given the appropriate sensors, the MFPD can be used in every phase of flight from pre-flight taxi to post-flight return to parking. Since it affords the means of controlling altitude (potential energy) and speed (kinetic energy), the MFPD is inherently an energy display. Thus, the continuous display of appropriate combinations of attitude, altitude, speed, and direction (and their respective rates) for the mission path of the moment is assured. For example, mission requirements permitting, the MFPD will provide trajectories that yield maximum range whenever we are in the CRUISE or NAV mode, maximum endurance in the HOLD or LOITER mode, and minimum time/energy conservative flight in either AIR-TO-GROUND or AIR-TO-AIR modes.

If we are to enjoy all these benefits of the MFPD, however, we cannot lose it from our display. Indeed, we cannot deviate very far from the path before the validity of its commands begins to suffer. A feature we call the "transition path" ensures that we always have an MFPD which is valid. A window of maximum acceptable deviation is established about the path. Whenever our deviation exceeds that limit, a new MFPD that takes us back to the prevailing mission path is generated. Thus, whether our deviations are intentional or accidental, we are never without the correct MFPD information.

Separate demonstrations by Northrop and the Navy have established that the MFPD will afford instrument flight that is approximately an order of magnitude more precise than that now possible with conventional cockpit instrumentation.

In conclusion, the MFPD should provide impressive increases in both operational effectiveness and flight safety, with concurrent reductions in crew training and system life cycle costs. The concept can be implemented with presently available hardware and, with customer support, could be operational within three years.

AIRCRAFT LIGHTING CONSIDERATIONS FOR FORMATION FLYING

Mr. Jeffrey Craig
AAMRL/HED, Wright-Patterson AFB, Ohio

BIOGRAPHY

Mr. Craig is an Industrial and Systems Engineer within the Human Engineering Division of the Harry G. Armstrong Aerospace Medical Research Laboratory. Working primarily in systems applications, he has been instrumental in the design, installation, flight test, and evaluation of several test systems in support of night special operations. Included among these systems are Night Vision Goggle compatible lighting configurations, Night Vision Goggle Head-Up Displays, and external strip lighting for aerial formation and refueling.

Aviation - Green electroluminescent (EL) strip lighting for night operations - requirement increasing AF-wide.

Aircraft lighting - requirement depends on ambient light levels.

Incandescent lights - poor attitude (Fig 1)

- Used on majority of today's aircraft
- Point source
- Provide poor indication of aircraft attitude for multi-ship formation.

Strip Lighting - (Fig 2)

- Strip lighting such as electroluminescent (EL) lighting is an excellent source for recognizing target aircraft attitude because of its application as an area source.

- Currently used on some of today's aircraft, e.g., F-4, F-15.

- Design criteria:

  - Flight path basic arrow effect
  - Direction
  - Relative attitude

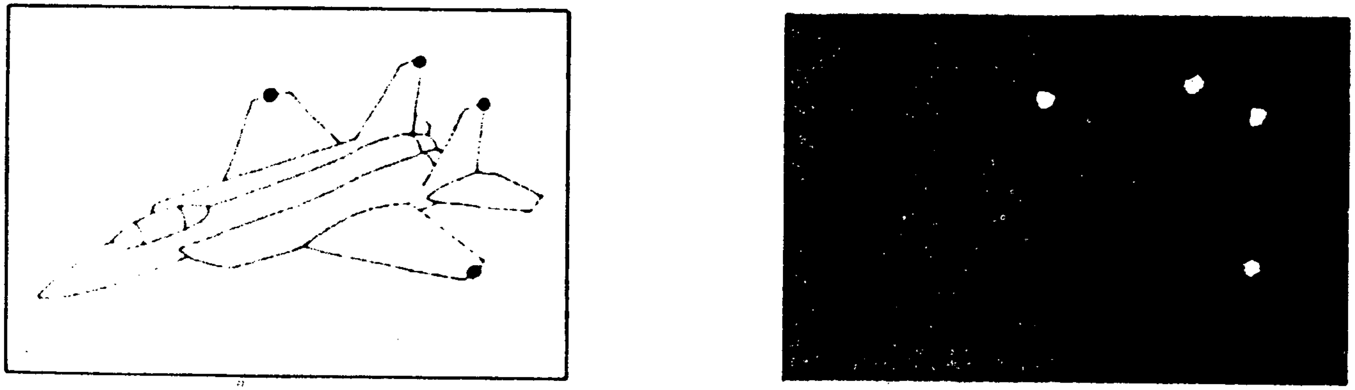
- Specific night requirements
  - Designer should research the mission requirements extensively before installing lights.
    - Don't just put them where they look pretty
    - Proper application is often neglected
  - Know everything about the mission (e.g., pilot interviews, flying in aircraft).
    - In addition, know aircraft structure before configuring the lighting.
      - Don't cover access panels; airstream deflection problems should be analyzed.
    - Skin of the aircraft - how to attach lights?
      - Weld, bond, rivet, etc?
  - Mission analyses: e.g., A-10 lead and wingman positions during a close air support mission.
  - Mission Planning Factors - Identify the applicable mission factors:

A-10	Comments
o Visibility	3 NM adequate formation visibility
o Symmetrical marking required	Any aircraft may have to serve as lead at any time or move to right/ left echelon
o Inflight refueling	No requirements
o Covertness	Use minimum number of lights and intensities in full moon to no moon condition. Formation safety is the critical tradeoff condition
o Long Range Acquisition	No strip lighting requirement for this: they would just use existing lighting
o Wingman Considerations	Try to design using normal daytime visual cues

- Inflight or simulator evaluations: (Fig 5).
  - Estimate range, direction, angle
- Question/Answer period
  - Aviation green EL lighting is the color used on most aircraft
  - Don't have to use EL strip light but advantage is that it is not subject to catastrophic failure like other strip light sources would be.
  - Soft glow off EL lighting is well liked by pilots.
  - HC-130 EL lighting test mod designed for Night Vision Goggles (NVGs) and naked eye use - test results indicate it might be improved by moving the EL lighting toward red end of light spectrum.
  - Stealth: Incandescent lights cannot be turned down nearly as far as EL lights can and still be visible.
  - Methods of design are questionable when reviewing today's aircraft already equipped with EL strip lighting.
  - EL lighting can also be used in the cockpit to reduce glareshield reflections and to achieve night vision goggle compatibility.
  - EL formation light levels range from 15 ft-lamberts for acquisition to 1 ft-lambert for close formation.

INCANDESCENT LIGHTING

- THE MAJORITY OF TODAY'S AIRCRAFT STILL FLY WITH INCANDESCENT (POINT SOURCE) LIGHTING
- POOR INDICATION OF AIRCRAFT ATTITUDE FOR MULTI-SHIP FORMATION



DAY

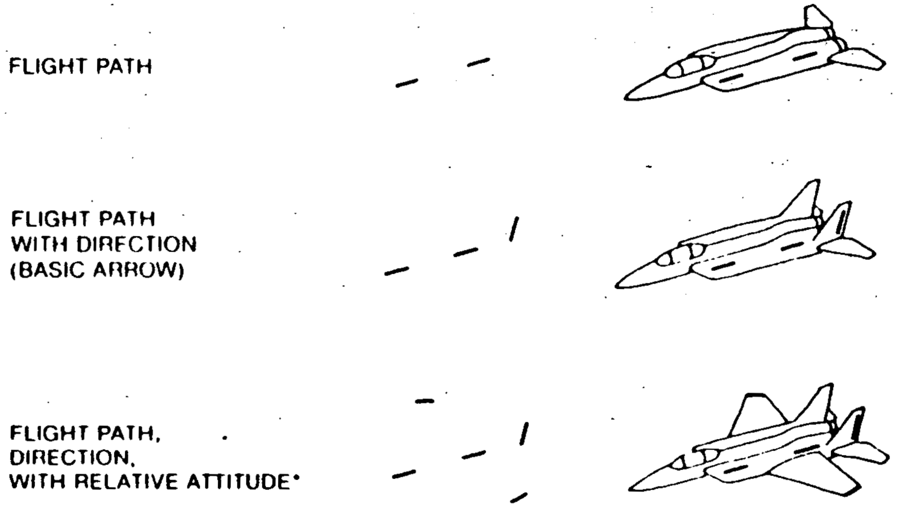
NIGHT

HE-85-10-6

Figure 1

STRIP LIGHTING

- STRIP LIGHTING (SUCH AS ELECTROLUMINESCENT LIGHTING) IS AN EXCELLENT SOURCE FOR RECOGNIZING TARGET AIRCRAFT ATTITUDE BECAUSE OF ITS APPLICATION AS AN AREA SOURCE
- CURRENTLY USED ON SOME OF TODAY'S AIRCRAFT



*TARGET ATTITUDE RELATED TO OWN ATTITUDE

HE-85-10-4

Figure 2

MISSION PLANNING FACTORS

- DESIGN USING DAYTIME VISUAL CUES WHEN APPLICABLE

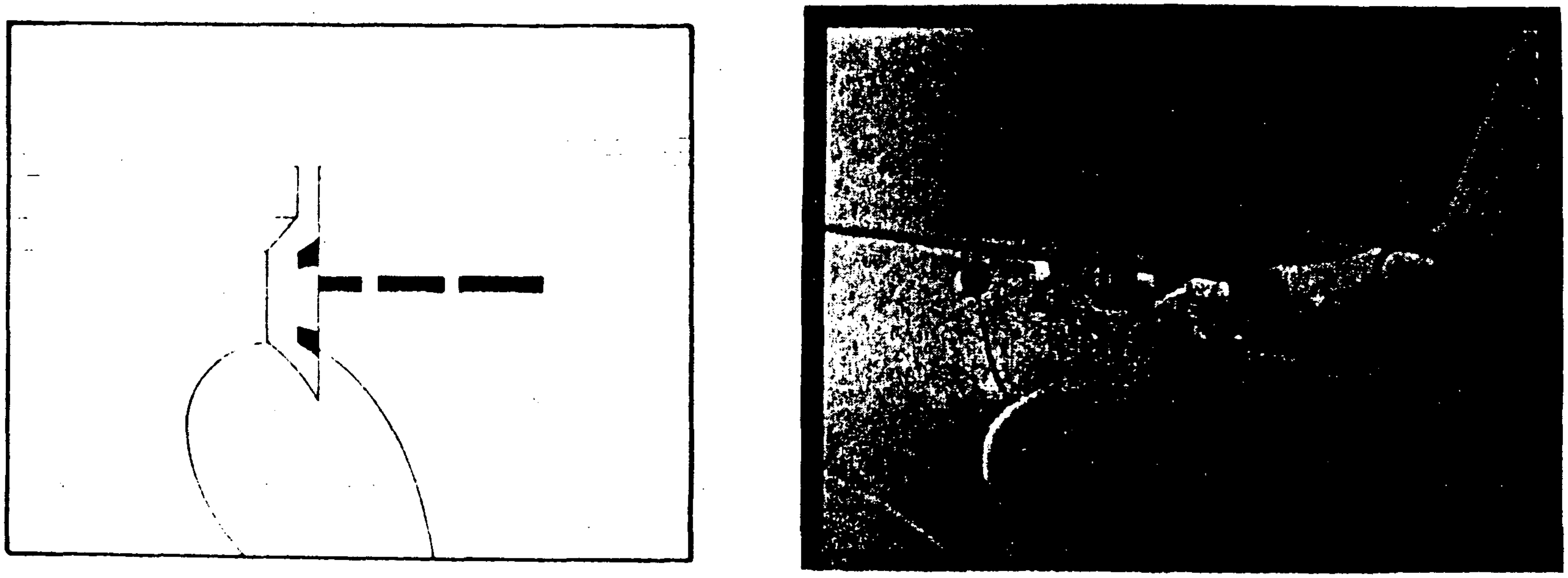
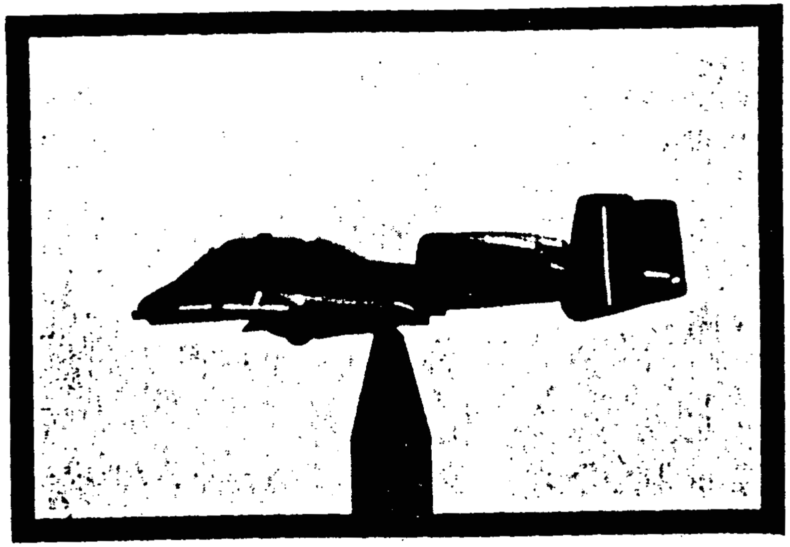
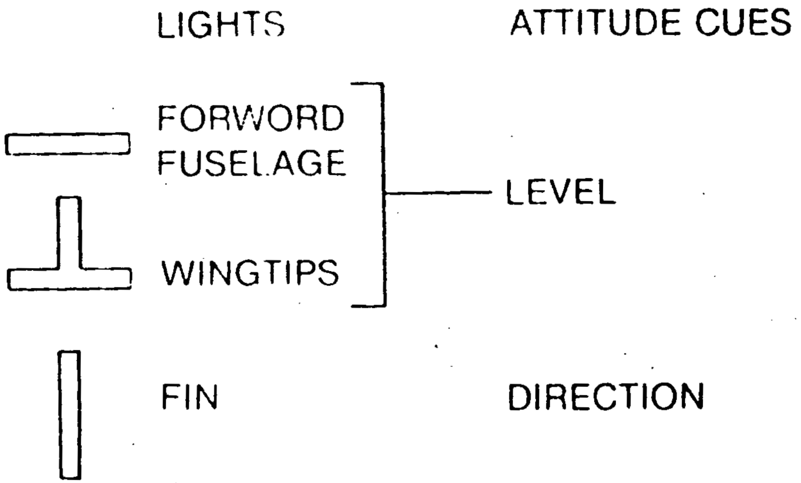


Figure 3: The line up cues on HC-130 aerial refueling pod for helicopters: uses three lights on flap intersecting two vertical lights on fuel pod strut.

VISUAL CUE GEOMETRY



FINGERTIP POSITION



LIGHTS

ATTITUDE CUES

FORWORD FUSELAGE

WINGTIPS

LEVEL

FIN

DIRECTION

Figure 4: Visual cue geometry, e.g., fingertip position for the A-10.

HE-85-10-7

INFLIGHT OR SIMULATOR EVALUATIONS

USE **2 CONFIGURATIONS**

- DARKROOM MODEL
- COMPUTER GENERATED
- INFLIGHT

HAVE PILOTS ESTIMATE **RANGE DIRECTION ANGLE** OF BOTH CONFIGURATIONS

HAVE PILOTS RATE **EACH LIGHT**

- ACQUISITION RANGE
- CORRECT ATTITUDE

HE-85-10-12

Figure 5

EFFECT OF GLARE AND REFLECTIONS ON AIRCRAFT ATTITUDE AWARENESS

Dr. H. Lee Task
AAMRL/HEF, Wright-Patterson AFB, Ohio

BIOGRAPHY

Harry Lee Task has been employed as a research physicist in the field of optics at the Armstrong Aerospace Medical Research Laboratory (AAMRL), Human Engineering Division since 1971. His research interests and efforts include display image quality measurement and assessment, helmet mounted displays, night vision imaging devices and aids, aircraft windscreen optical quality measurement, and human visual performance. He has authored many papers and articles and holds several patents in these and related areas. He is a member of the Optical Society of America and the Human Factors Society. He received his B.S. Degree in physics from Ohio University in 1968, M.S. in physics in 1971 from Purdue University, the M.S. and Ph.D. in Optical Sciences from the University of Arizona Optical Sciences Center in 1978, and the M.S. in Management of Technology in 1985 from the Sloan School of Management, Massachusetts Institute of Technology.

INTRODUCTION

AAMRL has been involved in a number of research efforts that relate to the impact of glare and reflections on observer performance and perception. Although none of these efforts has directly addressed the effects of glare and reflections on aircraft attitude awareness it is obvious that if you cannot see outside the cockpit and you cannot see your instruments due to glare and/or reflections, then you will indeed have a problem with attitude awareness.

The terms "glare" and "reflection" are used quite often to describe a number of different effects. This paper describes several of these conditions. Table 1 is a listing of the topics discussed in this paper.

Table 1. List of topic areas discussed in this paper.

DAY	NIGHT
Windscreen haze "glare"	External relections
Solar "glare" from HUDs	Internal relections
Daytime "glare" reflections	Night Vision Goggles & glare
Possible solutions	

Figure 1

DAYTIME EFFECTS

Windscreen Haze

Modern military and civilian aircraft typically have plastic windscreens instead of glass. The plastic can be easily molded to aerodynamic shapes and is much lighter than glass. The military aircraft have switched to plastic because it is much tougher than glass and is able to withstand birdstrikes substantially better than glass. However, one of the drawbacks to plastic is that the optical quality of the transparency is not as good; in particular microscopic inclusions and small surface scratches cause a scattering of incident light.

This scattered light results in a veiling luminance that reduces the contrast of objects viewed through the windscreen. This effect is called windscreen haze. The degree of haze depends on many factors such as the number and density of surface scratches and internal scattering particles, the illumination intensity, the angle of the illumination with respect to the viewing angle and the luminance level of the scene viewed through the transparency.

If the haze is sufficiently bad it may totally obscure the view through the windscreen. This condition can occur when the aircraft is oriented toward the sun at sunrise or sunset (Fig. 1). Haze effects also increase with the age of the windscreen. As the windscreen ages and receives more microscopic surface scratches (many of these are due to cleaning procedures as well as impact with particles of sand, etc.) the haze increases.

It is apparent that if the haze is so bad that the pilot cannot see out of the transparency, then his ability to maintain attitude awareness via direct viewing of the outside world is greatly reduced. There have been methods developed to quantify the haze in the windscreen (Task & Genco, 1985) with the intent of developing standards for both accepting new windscreens and determining when used ones should be removed from the aircraft due to the level of haze.

HUD effects - haze enhancement

Aircraft heads-up displays (HUDs) use combiners to superimpose the HUD display image on the exterior scene as viewed through the windscreen. This combiner can also be a source of light scattering (haze) while at the same time reducing the luminance of the exterior scene which further enhances the contrast reducing haze effect (Compare Figs 2, 3, and 4).

Holographic HUDs such as the LANTIRN HUD may cause higher levels of haze simply due to the dichromated gelatin of the hologram.

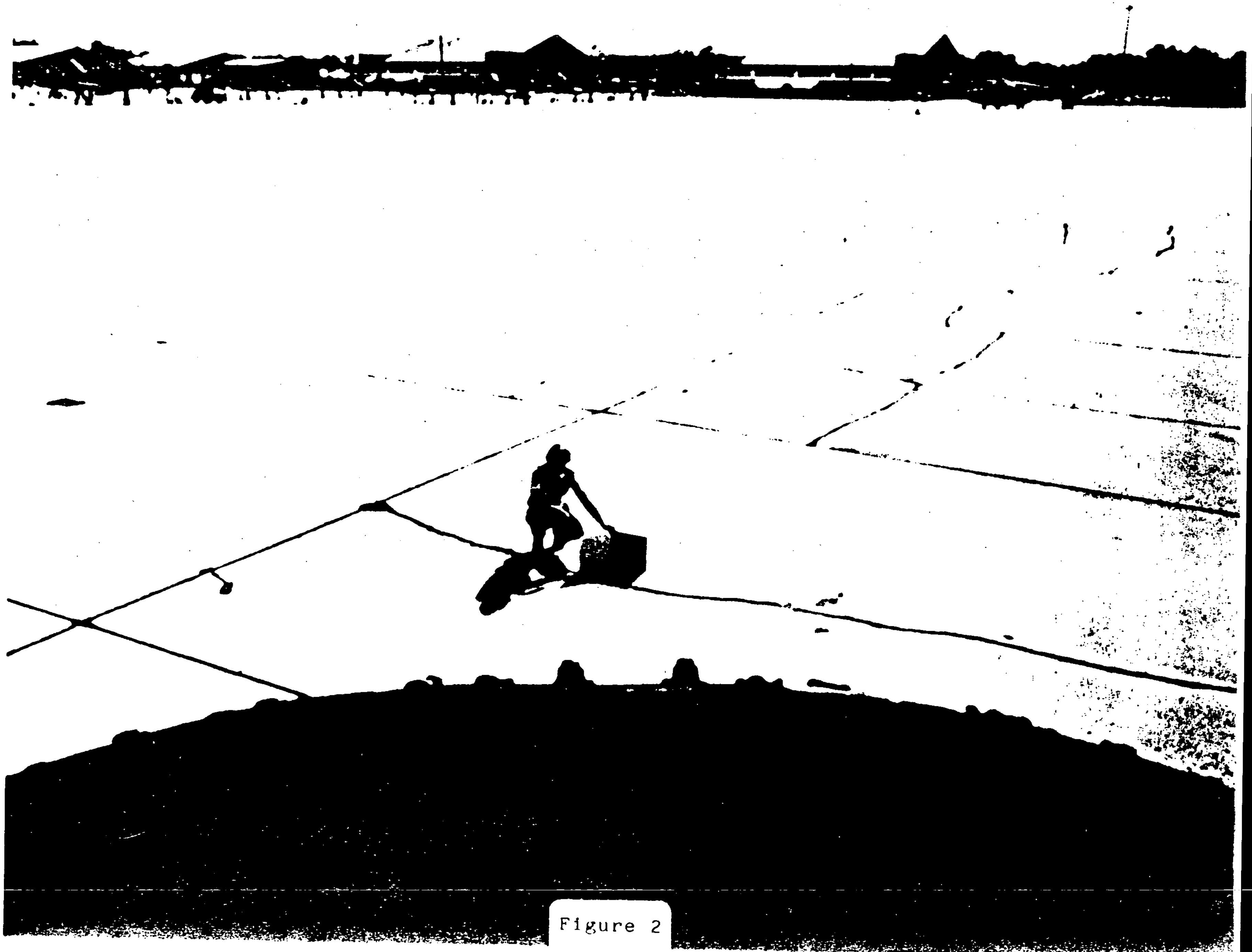


Figure 2

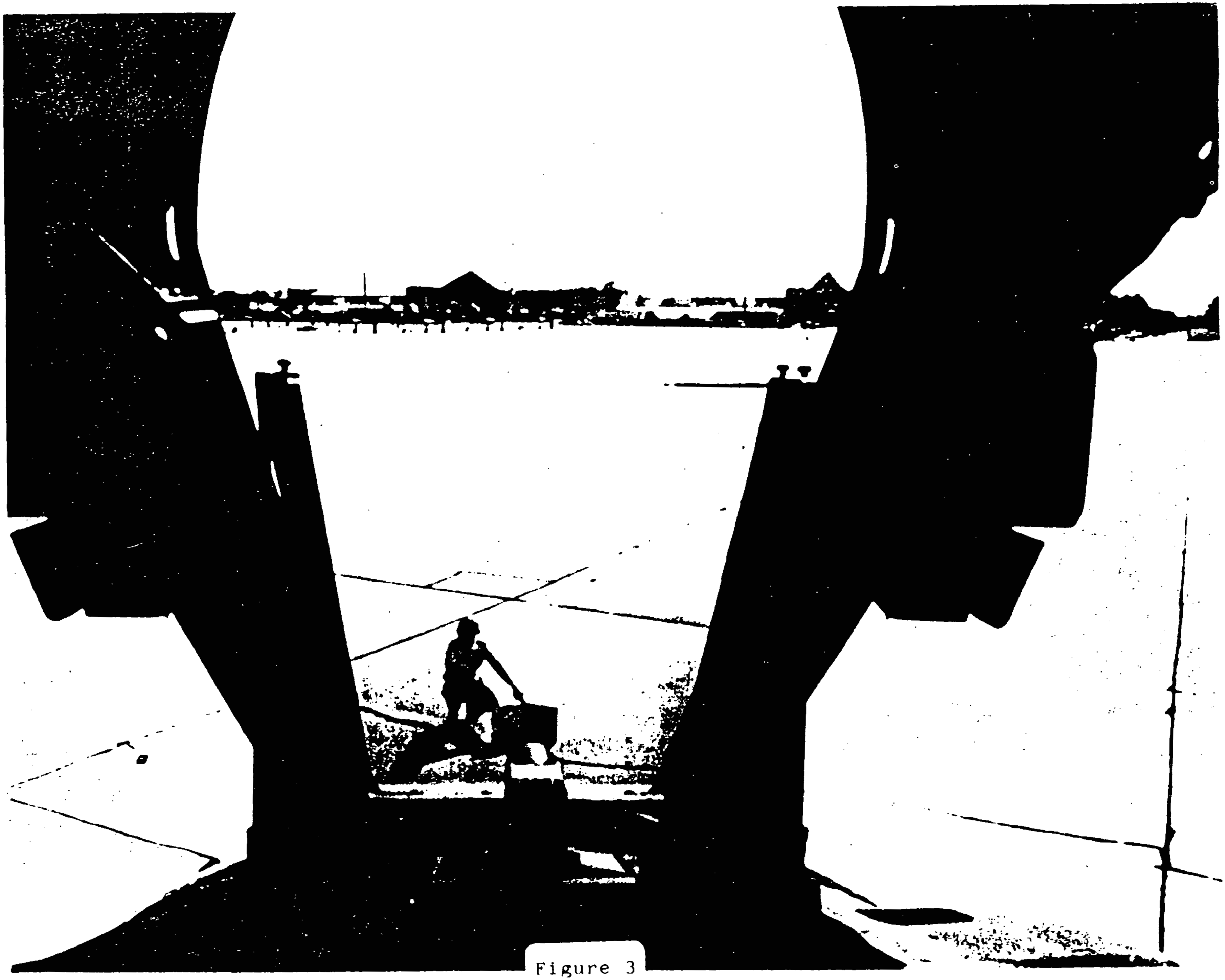


Figure 3

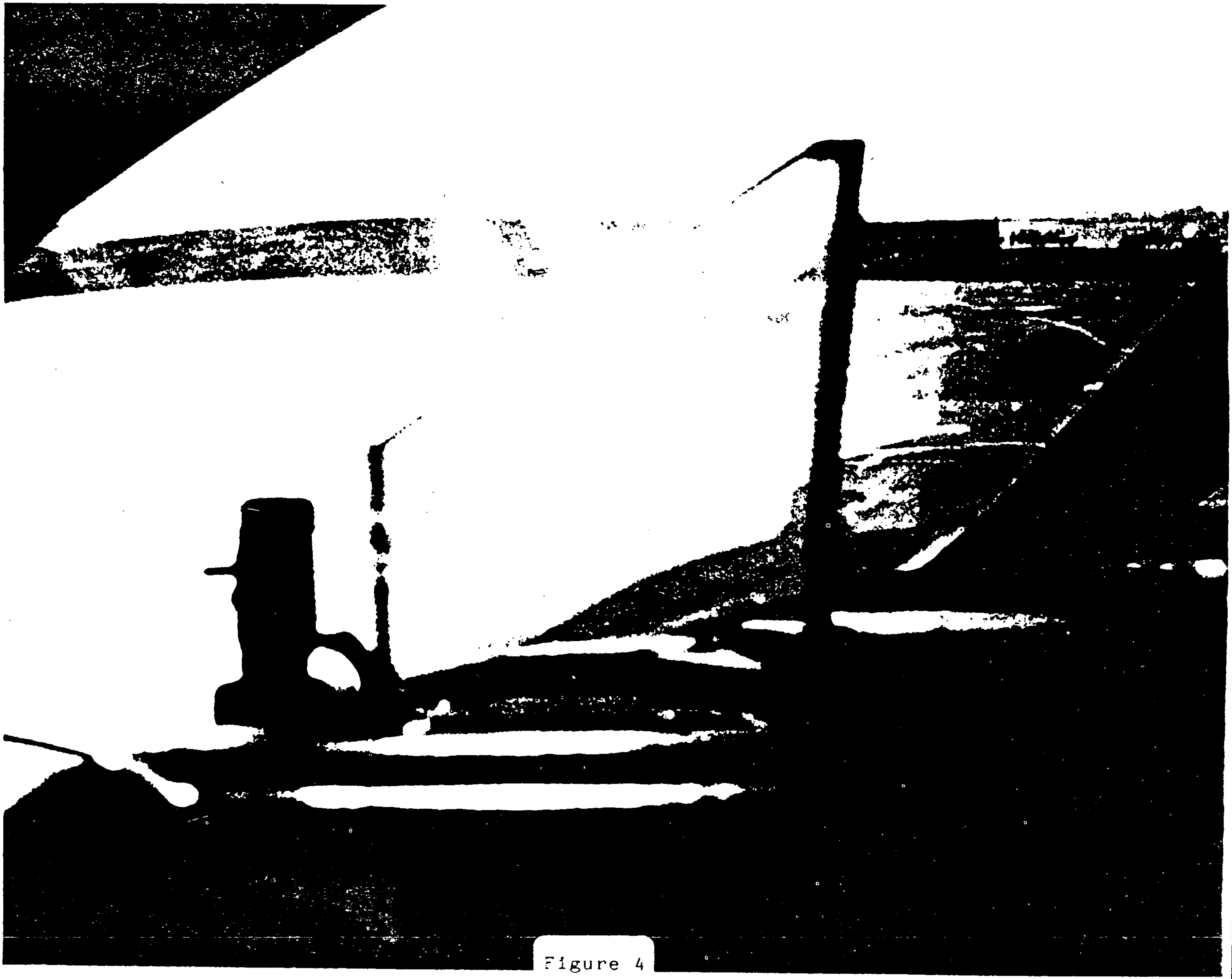


Figure 4

Daytime reflections

There are several reflection situations in aircraft cockpits that either reduce visibility throughtout the windscreen or reduce the viewability of the aircraft instruments. Reflections can be either specular (mirror-like) or diffuse (scattered; similar to haze except in a reflection mode). Three specific reflection problems are described in the following:

Windscreen reflections:

A common reflection problem is the reflection of various objects internal to the cockpit, illuminated by the sun, reflecting in the windscreen. Two specific examples of this are the reflection of the pilot's white helmet in the windscreen of the F-16 and the reflection of the glare shield in the windscreen of most aircraft (Fig 5). The glare shield reflection is particularly irritating; the reason the glare shield is painted black is to reduce this reflection. However, as dust and dirt gathers on the glare shield the diffuse reflectance of the surface can increase substantially resulting in as much as an additional 10-15 % loss of contrast viewing through the windscreen.

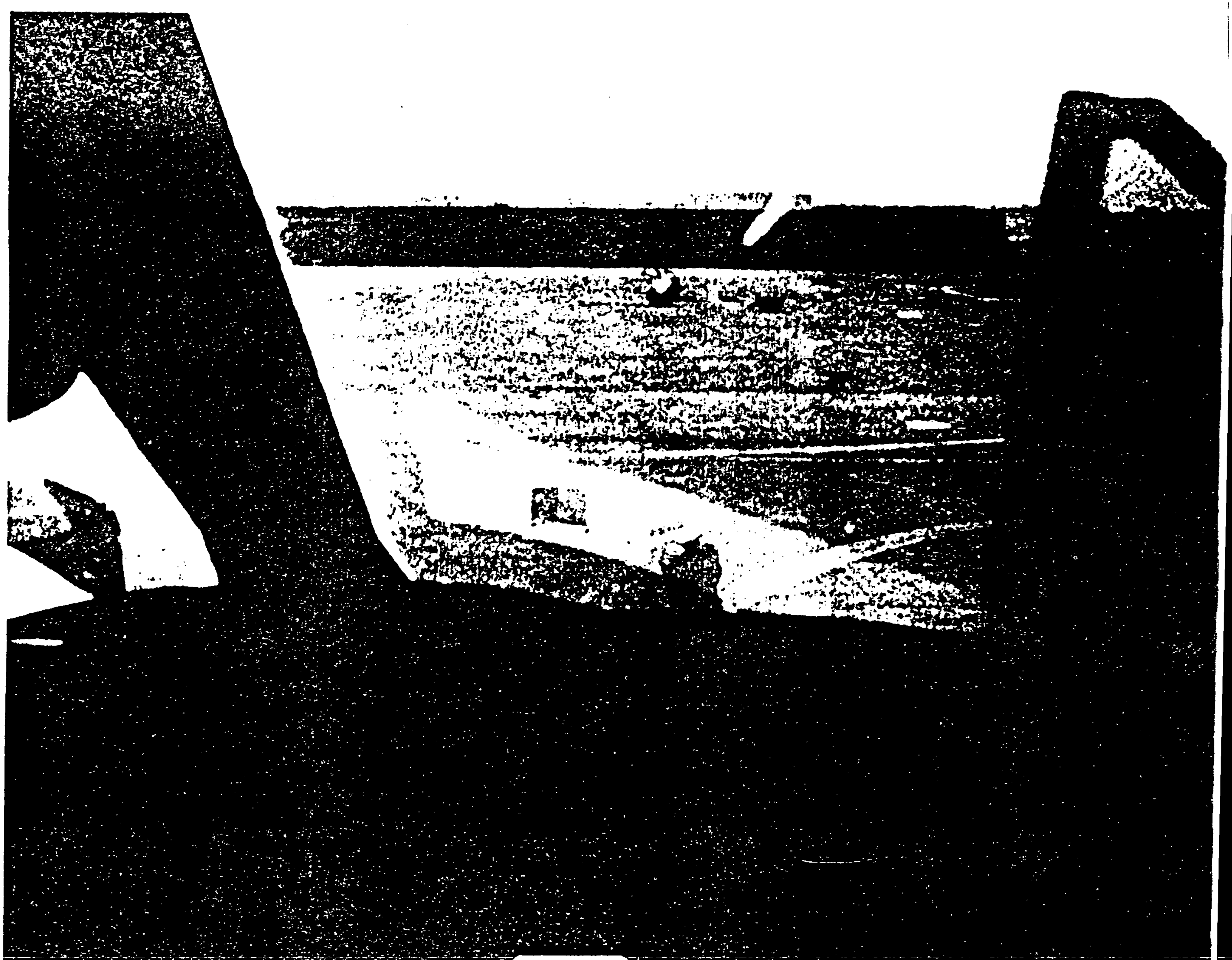
Sun reflections off the HUD:

The LANTIRN HUD is designed using three holographic lenses. These are arranged in such a way that the pilot must view through all three of these in the upper or "eyebrow" region of the HUD. This area is therefore particularly bad from the standpoint of transmissivity and haze.

In addition, the LANTIRN HUD optical system is such that the sunlight can enter from the top through the eyebrow region and enter the optical chain in such a way as to produce a real image of the sun located part way between the HUD and the pilot. There are also two secondary smaller virtual images of the sun created in the lower region. These various images are quite bright and move in opposite directions as the aircraft changes orientation with respect to the sun. Thus these unwanted reflection-produced images can not only obscure HUD symbology, they can also provide a significant dynamic distraction in the pilot's critical forward field of view (Fig 6).

Sun reflections from aircraft instruments and displays:

Another daytime reflection problem occurs when sunlight illuminates aircraft instruments and displays. The illumination can result in both specular and diffuse reflections from cathode-ray tube (CRT) display phosphors and glass face plate as well as instrument cover glasses. These reflections can reduce contrast of the instruments and displays to a level where the information on the display or instrument is difficult or impossible to read (Figs 7 and 8).



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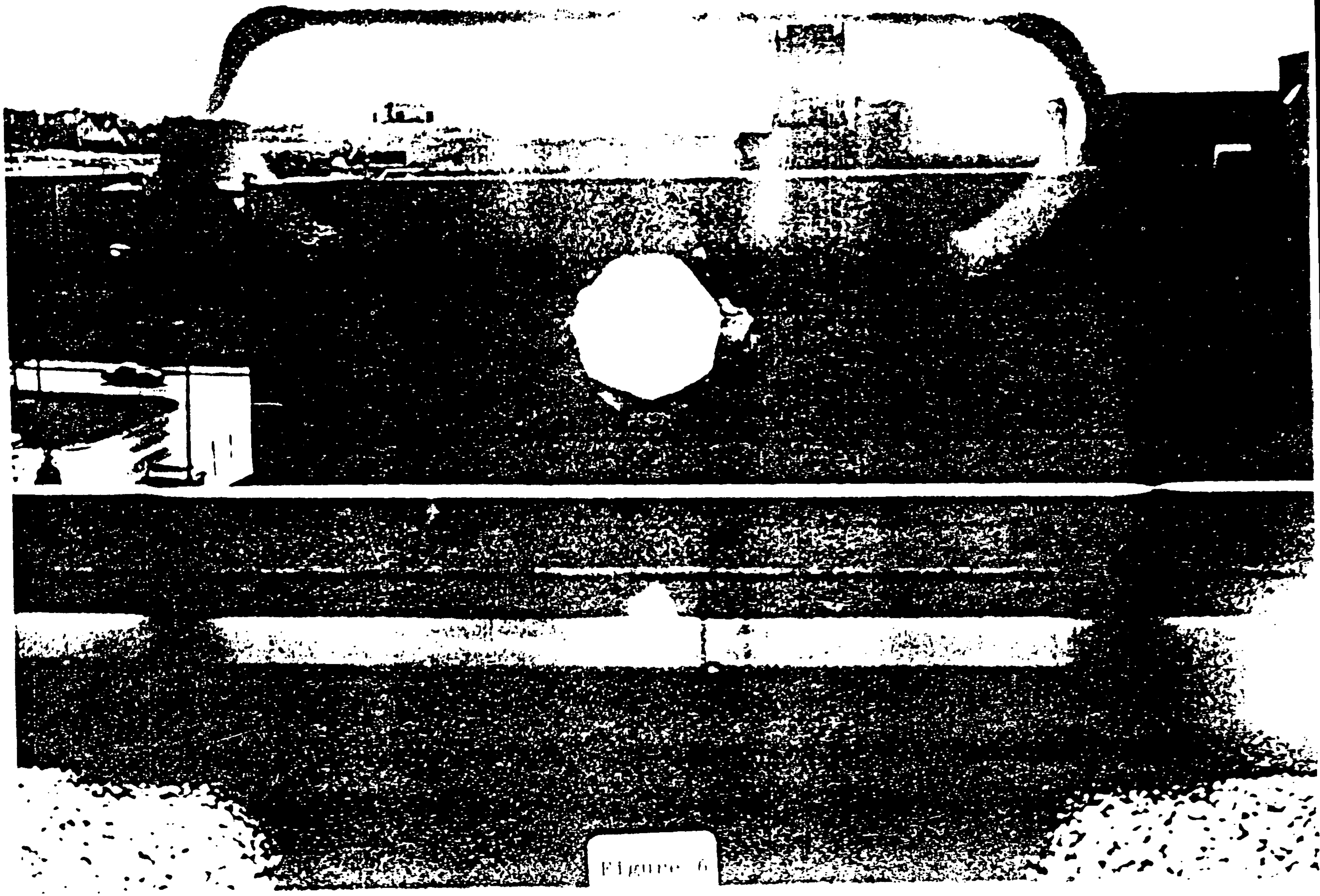

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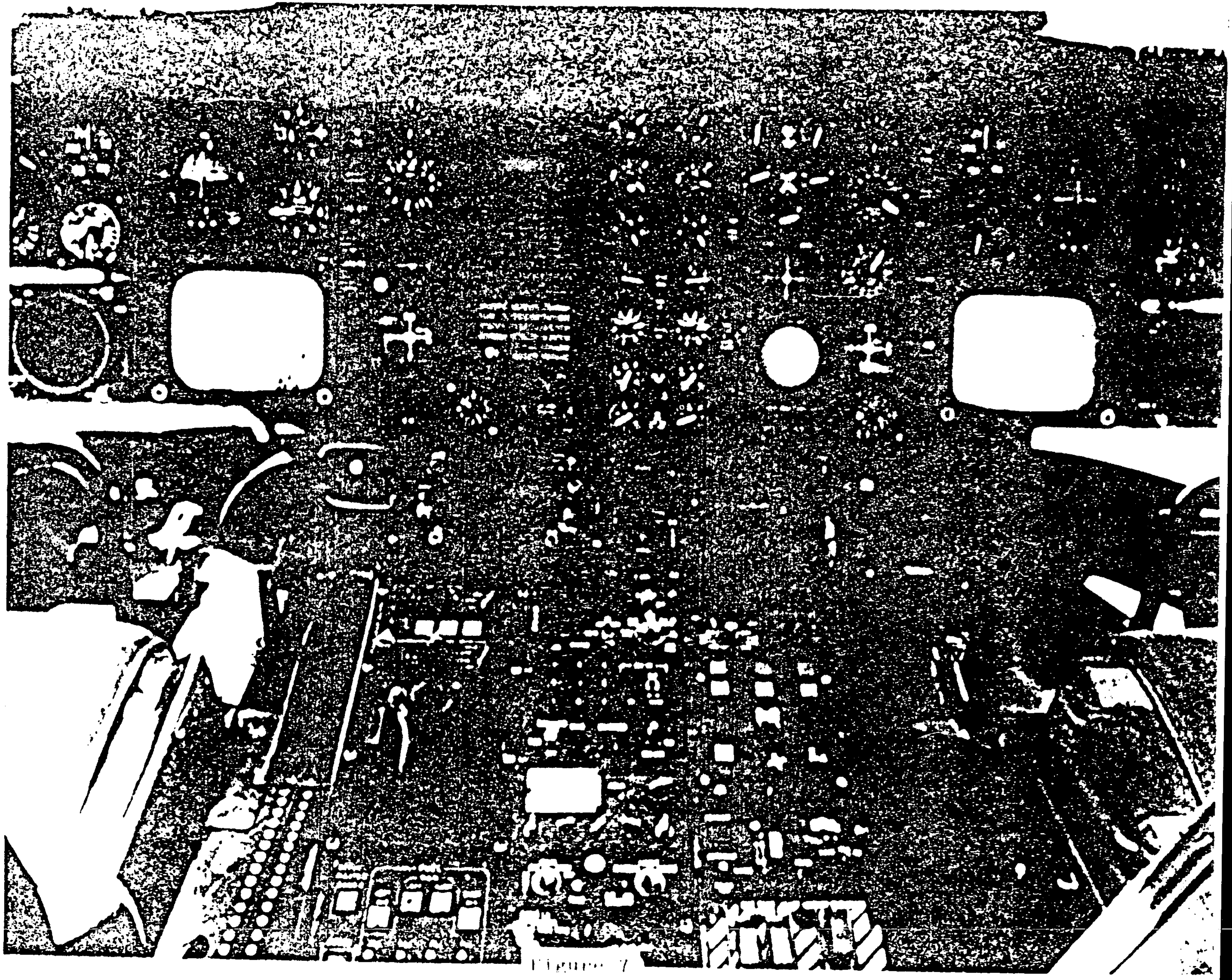

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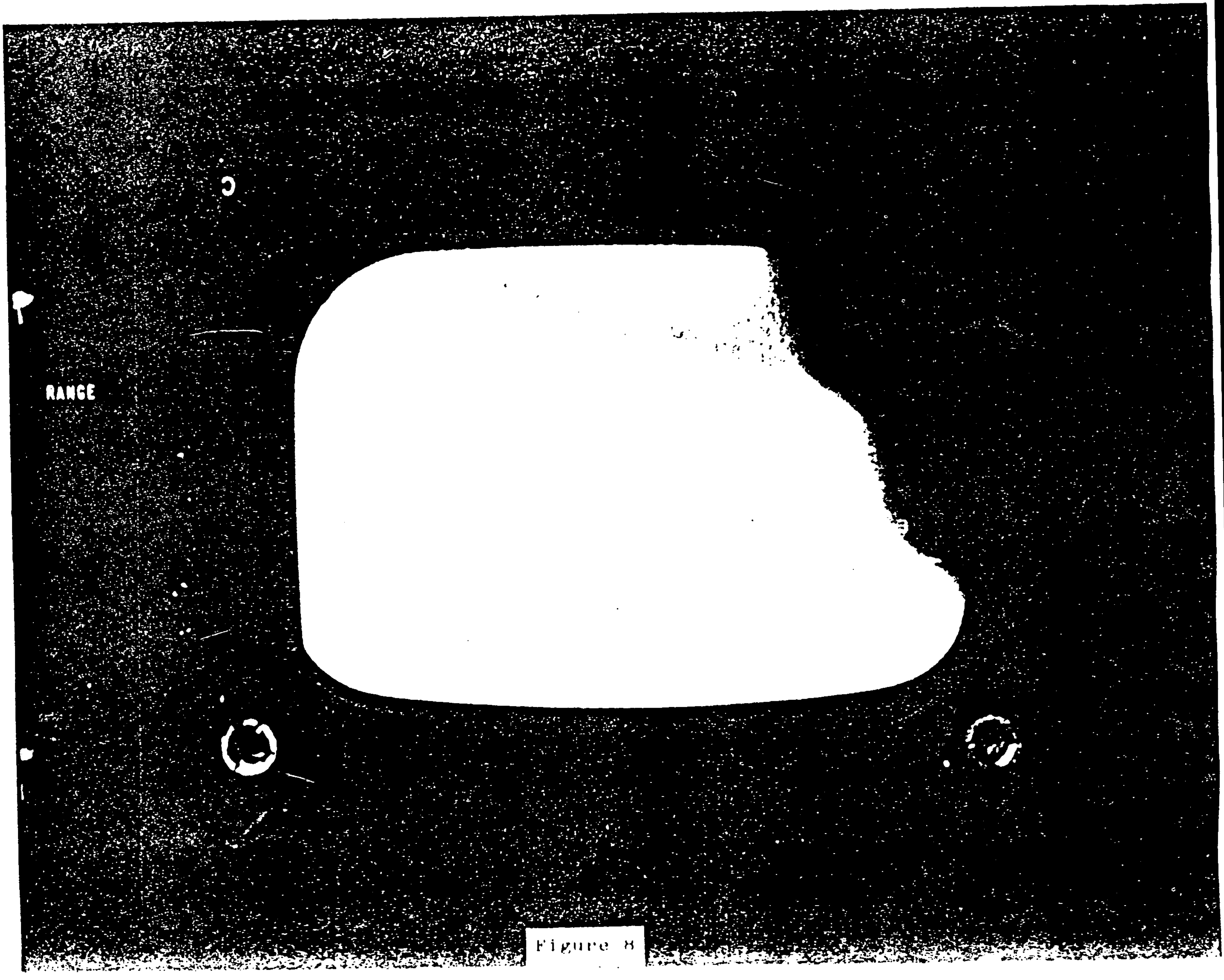


Figure 8

These effects can be reduced or eliminated with the appropriate use of contrast enhancement filters and glare shield design (Figs 9 and 10).

Solutions for daytime problems

* Use appropriate measurement methods and specification levels for controlling the degree of transparency haze allowed. This is for all transparencies including windscreens, canopies, helmet visors, gas masks, HUD combiners, etc.

* Set up routine maintainence and safety monitoring capability to determine when a transparency has reached a level of haze degradation that it should be replaced.

* Develop methods of cleaning or easily replacing aircraft glare shields to reduce the contrast reducing reflections in the windscreen caused by dusty glare shields.

* Use contrast enhancing filters for instruments and displays such as circular polarizer filters, color notch filters, neutral density filters with anti-reflection coatings, micro-louver (3M Co.) baffles (Fig 11), etc.

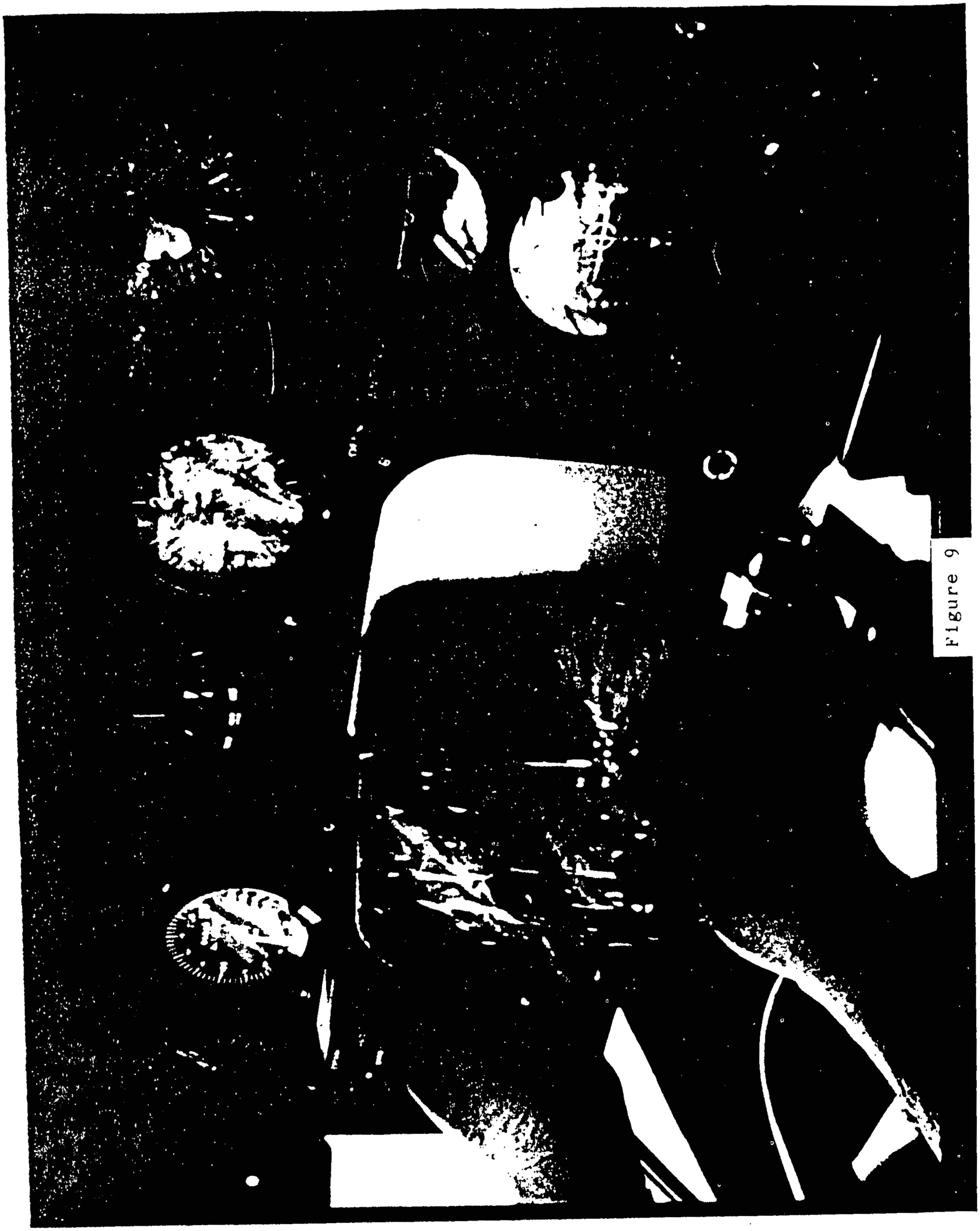
NIGHTTIME EFFECTS

As in the daytime situation there are several reflection conditions that occur and all are lumped into the same designations as reflection and glare problems. There are two broad areas of reflections that can be considered: internal reflecitons and external reflections. For purposes of this presentation, internal reflections are defined as any reflection that is caused by a light source internal to the cockpit and external reflections are any reflections that occur from light sources outside of the cockpit.

External reflections

There are two types of external reflections that have been noted. One, reported for the A-10, occurs during landing and take-off and is caused by the light from the runway marker lights entering the cockpit through the windscreen and then reflecting from the inside surface of the windsreen. This results in a distorted image of the runway marker lights appearing in the pilot's peripheral vision (Fig 12).

The second type of external reflection is also called multiple imaging. This results from light coming from the runway marker lights (or any other external light source, although the marker lights are the main cause for complaint) coming through the first (outer) surface of the windscreen, then some of the light reflecting from the second (inside) surface of the



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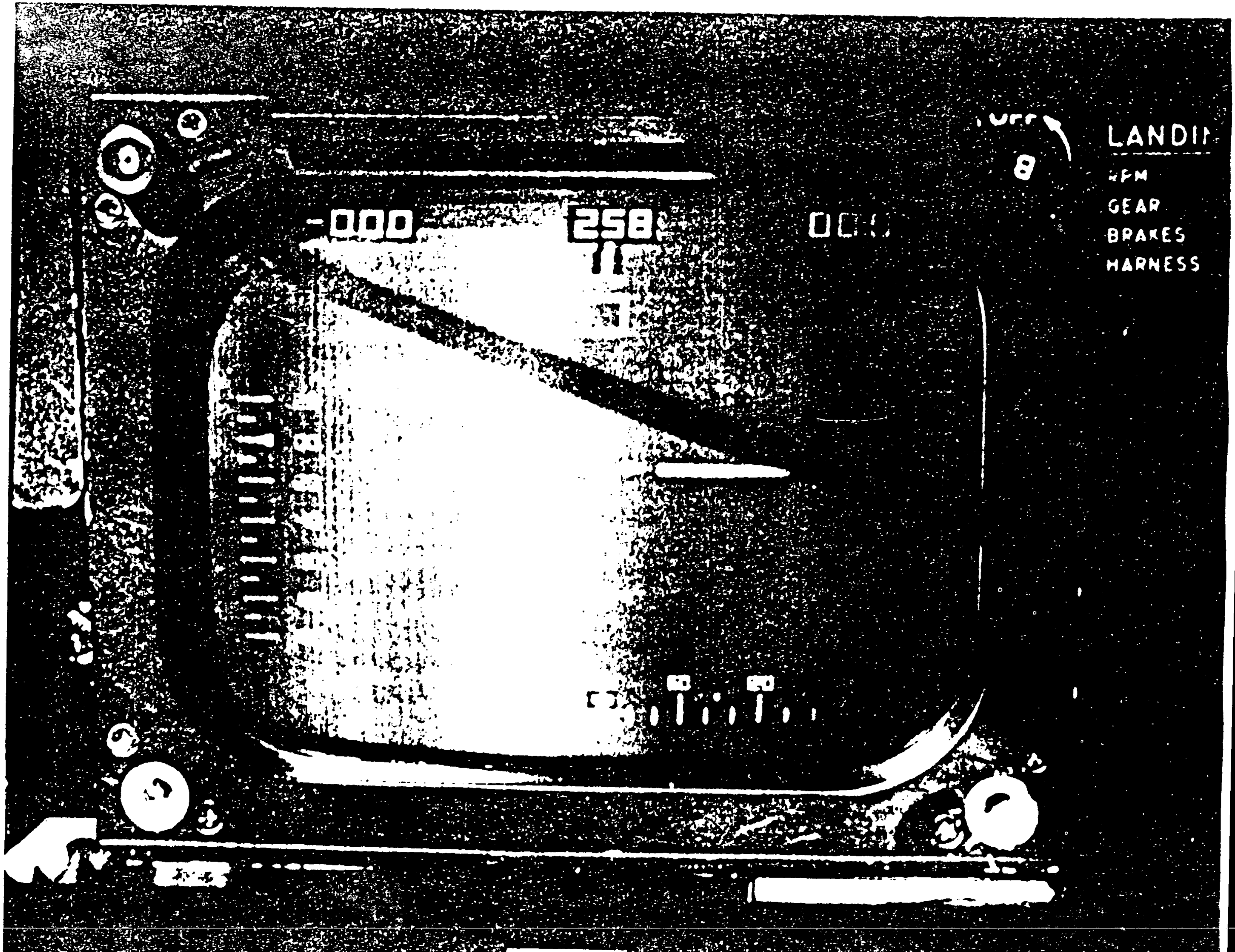

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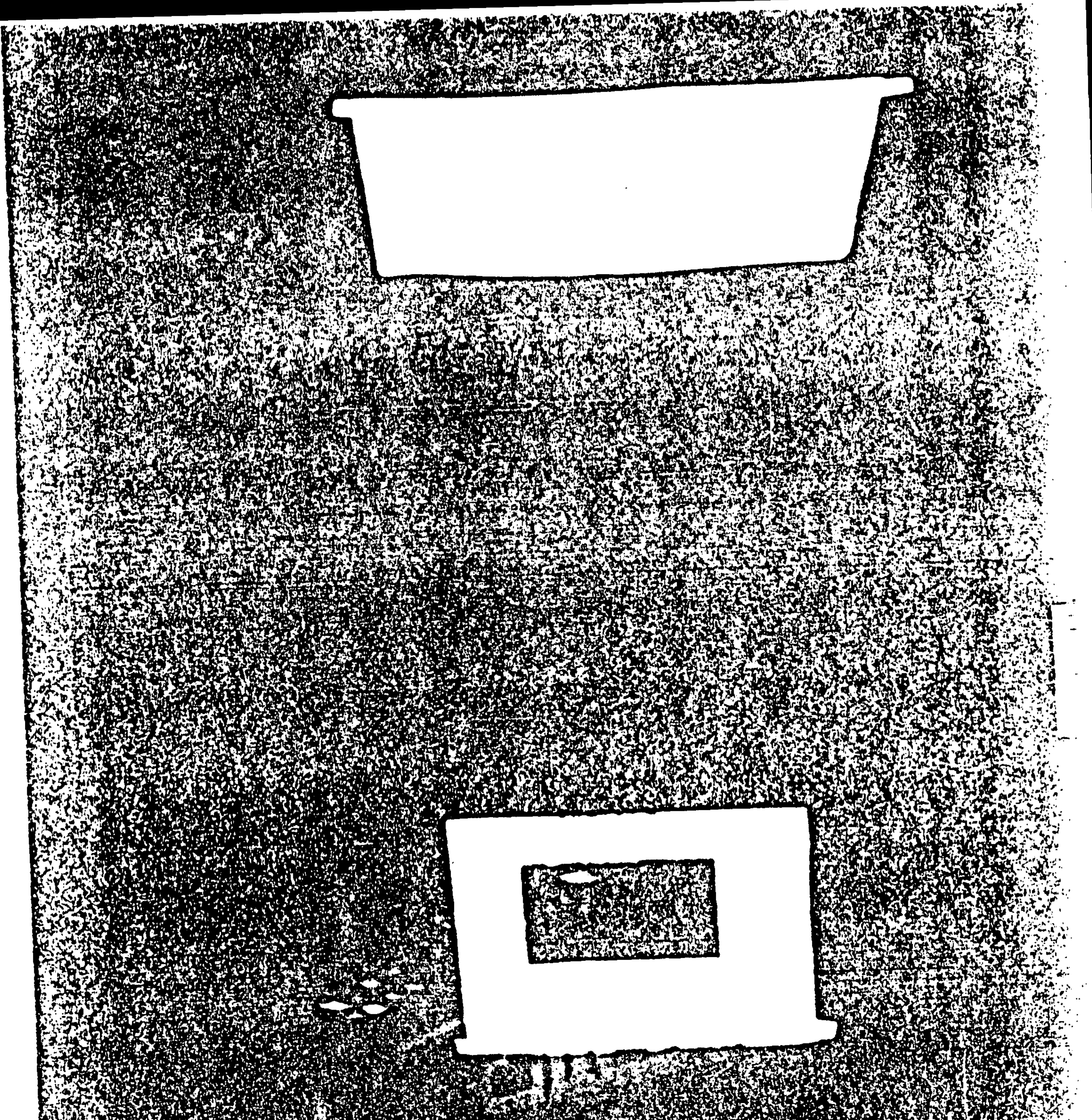


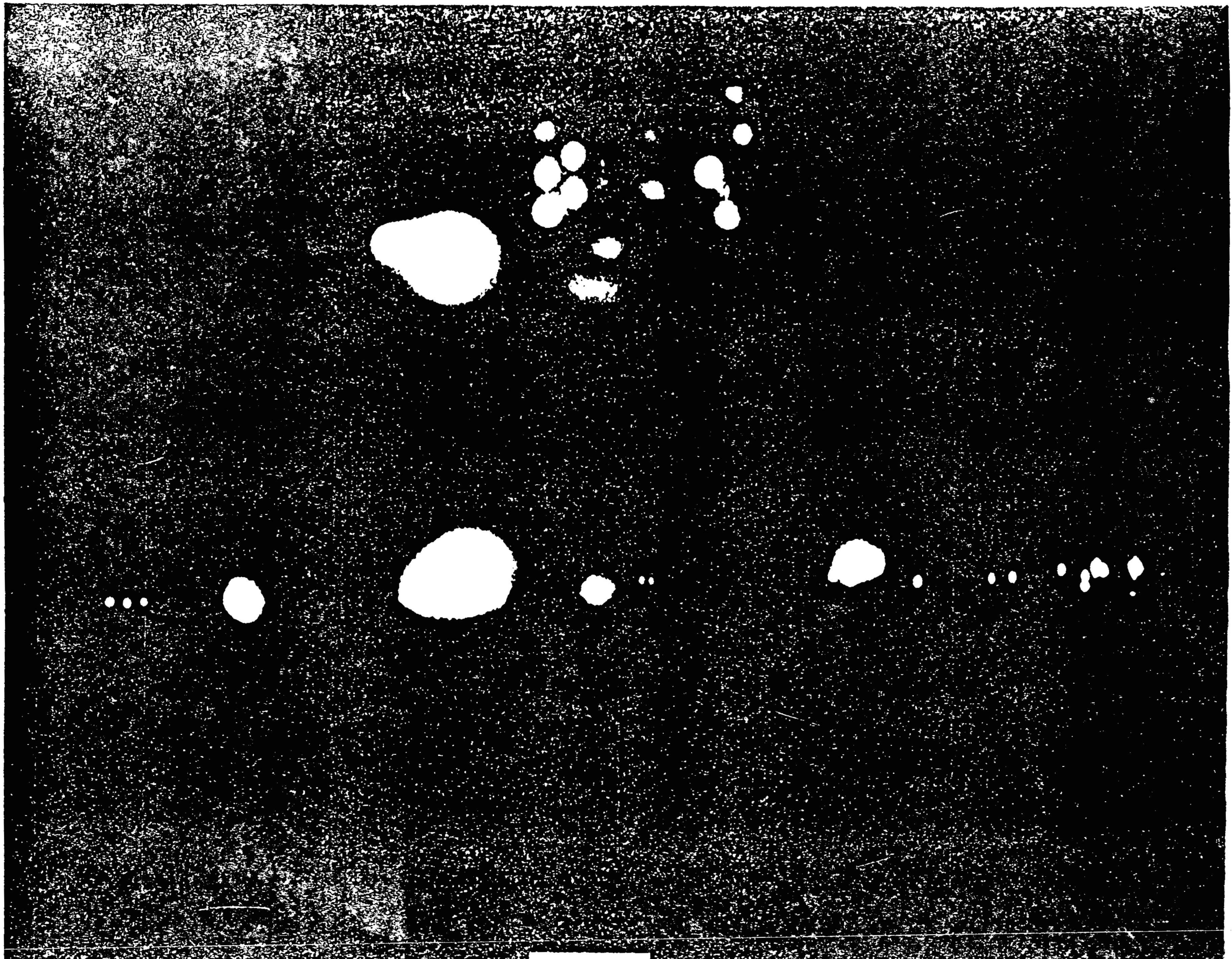


Figure 12

windscreen back to the first surface, then some of this light reflecting once again back toward the interior of the cockpit. This second ray of light produces a second image of the runway marker light. If the windscreen is of sufficiently high quality then the secondary image is formed on top of the primary (direct view) image of the runway marker light and the two are seen as a single light. However, if the secondary image is angularly shifted with respect to the primary then the pilot sees two rows of runway marker lights. The secondary image is typically much dimmer than the primary (by a factor of 20 or more), but due to the night situation the contrast of the secondary is essentially the same as the primary, making it very visible (Fig 13).

This effect of multiple imaging (there can be more than just a second additional image) occurs more frequently with the thicker, plastic, birdstrike resistant windscreens that are installed at rather steep angles. Complaints of multiple imaging have been reported for F-111 aircraft and B-1 aircraft. Methods of quantifying and developing acceptable limits of multiple imaging are now in progress at AAMRL for the B-1B aircraft windsreen (Figs 14 and 15).

Internal relfections

Internal reflection complaints occur when cockpit instruments and displays are positioned such that an image of the illuminated (or emitting) instrument or display is visible in the windscreen. Both inner and outer surfaces of the windscreen reflect a portion of the light incident on the windscreen from the illuminated instruments and displays (Figs 16 and 17). Thus the intensity of the reflection is approximately half due to the inside surface and half due to the outside surface of the windscreen. It is this fact that makes it extremely difficult to correct this problem by treating the windscreen. There have been discussions of coating the inside surface of the windscreen with an anti-reflection coating to reduce the internal reflections. This is a very difficult process due to the angle dependence of anti-reflection coatings and the size of the plastic windscreens. Even if such a coating were possible and totally successful, it would reduce the intensity of the reflection by only about 50% because the outer surface will still be reflecting the light. Since the outer surface is subject to a rather severe environment (weather, sand abrasion, cleaning, etc.) it is highly unlikely that an acceptable coating process will be developed for the exterior surface.

The best way to reduce internal reflections is to simply insure that the light cannot reflect in the windscreen. This can be done by using various methods to direct the light toward the pilot and away from the windscreen. On some aircraft (such as the F-16) this might be difficult because of the considerable amount of windscreen area and the "wrap-around" nature of the windscreen.

Another possible method of reducing the internal reflections caused by instruments and displays that are located such that it is difficult to properly baffle them is to polarize the light coming from the instrument or

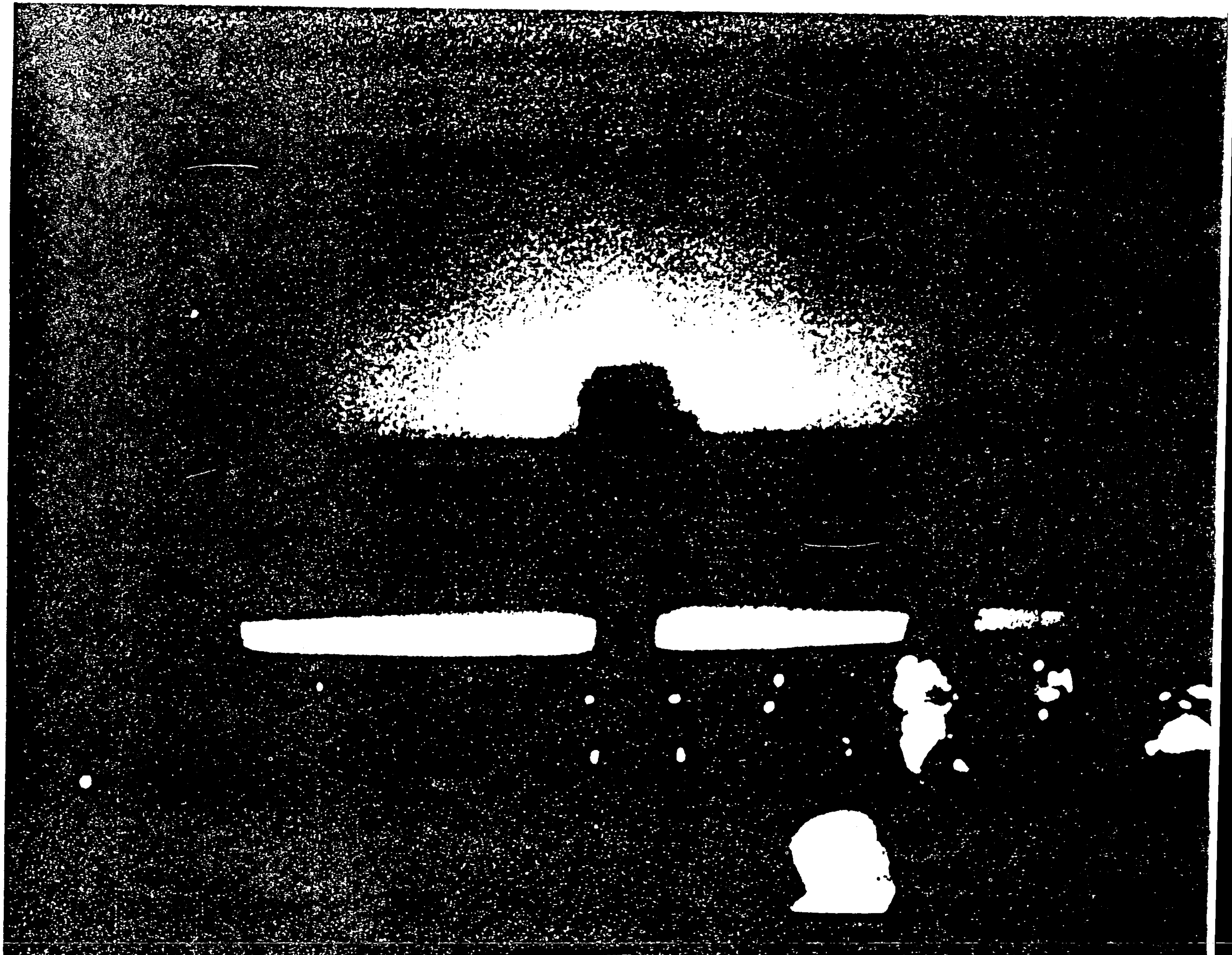
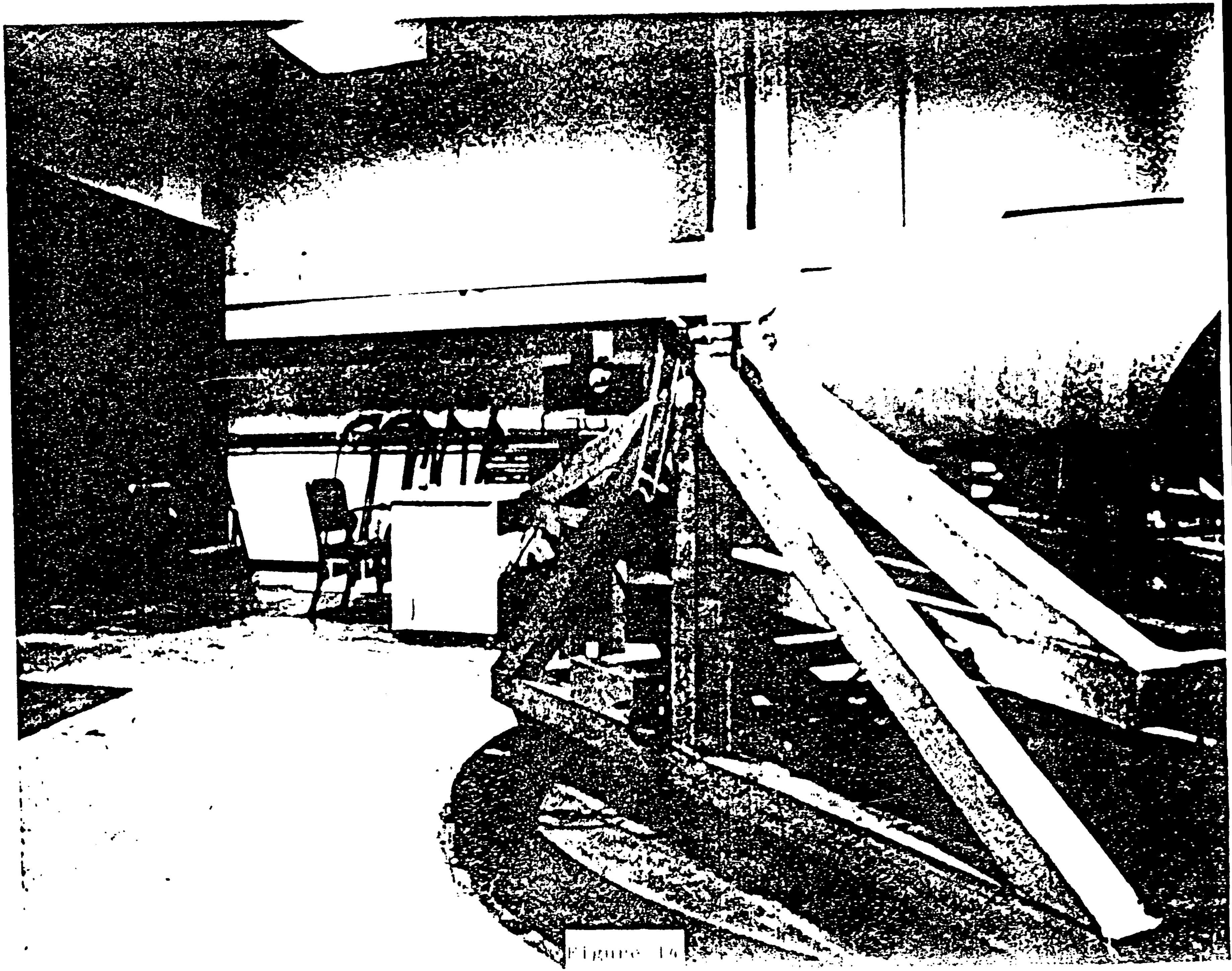


Figure 13



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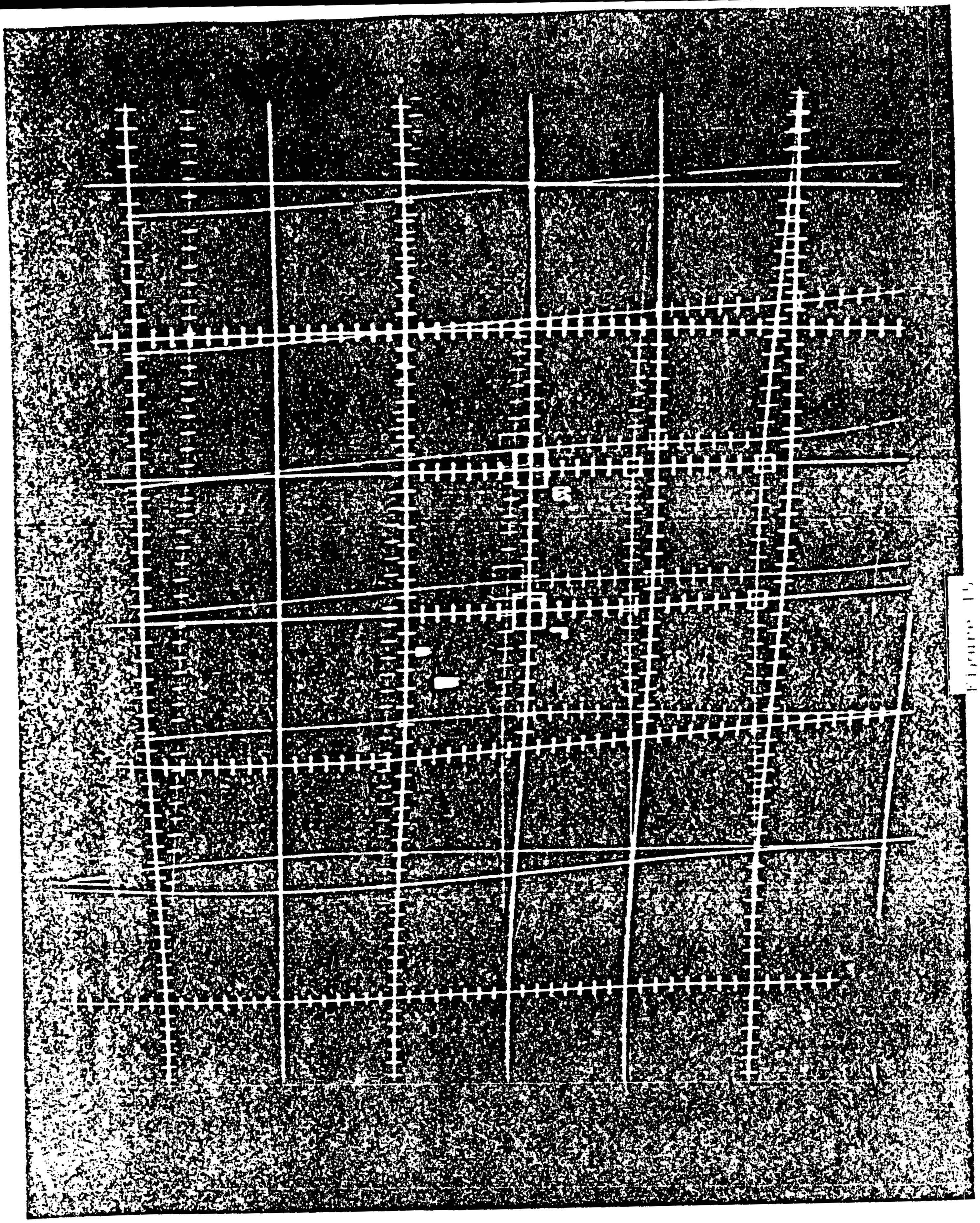


Figure 15

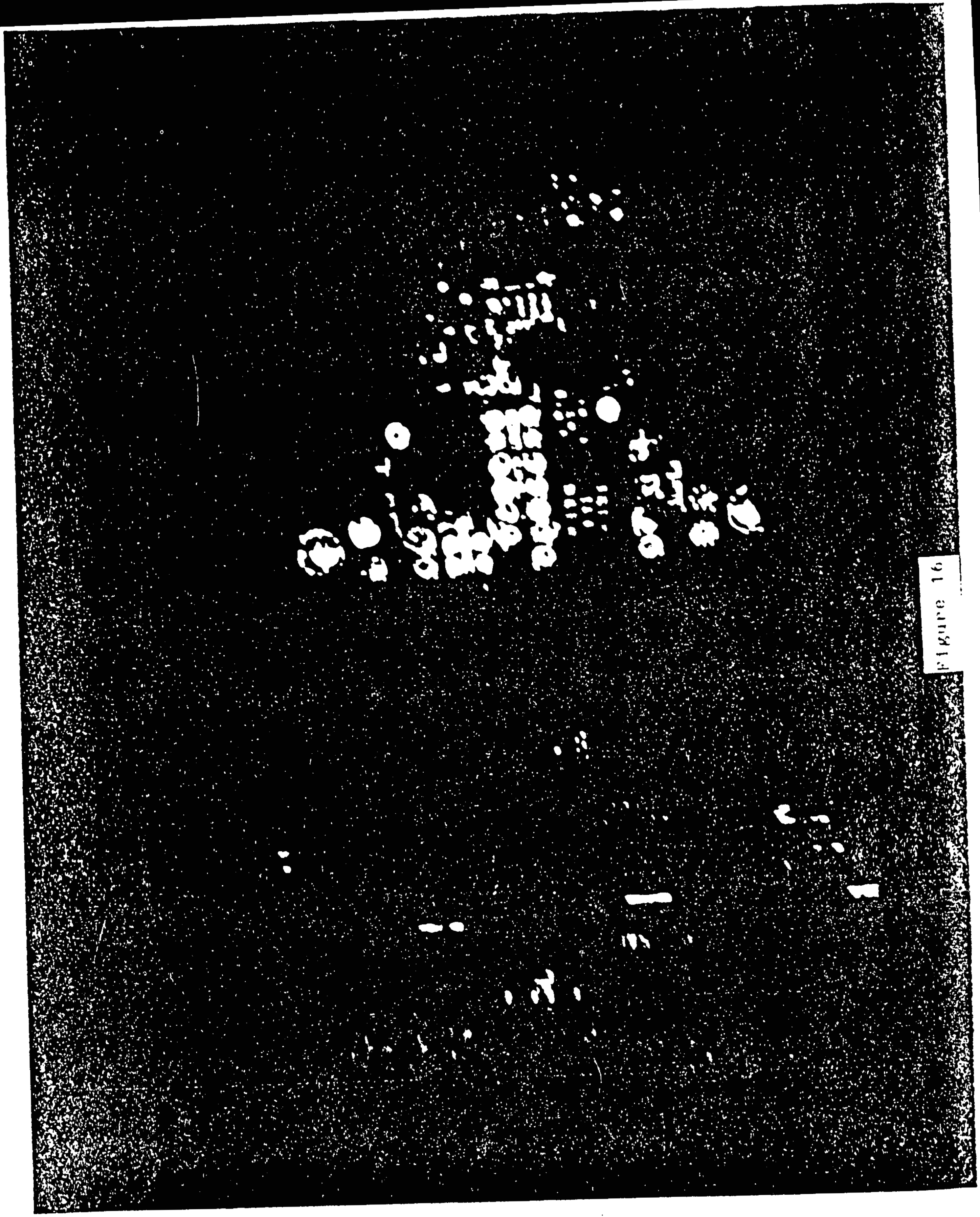


Figure 16

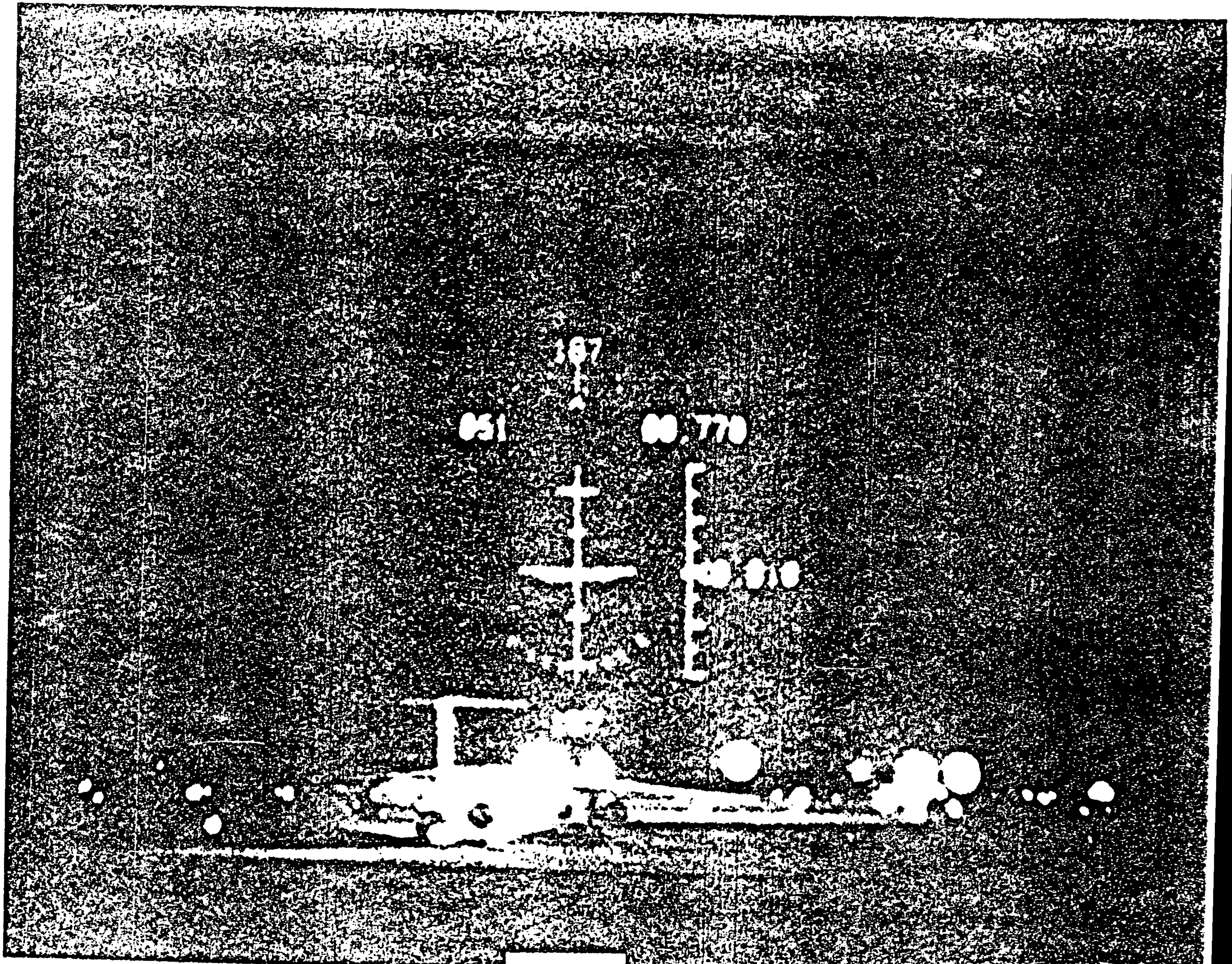


Figure 17

display. When viewed at an angle, surfaces of transparencies act like partial polarizers. The degree of polarization depends on the angle of view and the index of refraction of the material. By polarizing the light source in a direction approximately perpendicular to the natural polarization reflection direction of the transparent surface, it is possible to decrease the amount of reflection at both inside and outside surfaces of the transparency considerably (a 90% reduction for some angles has been demonstrated in the lab).

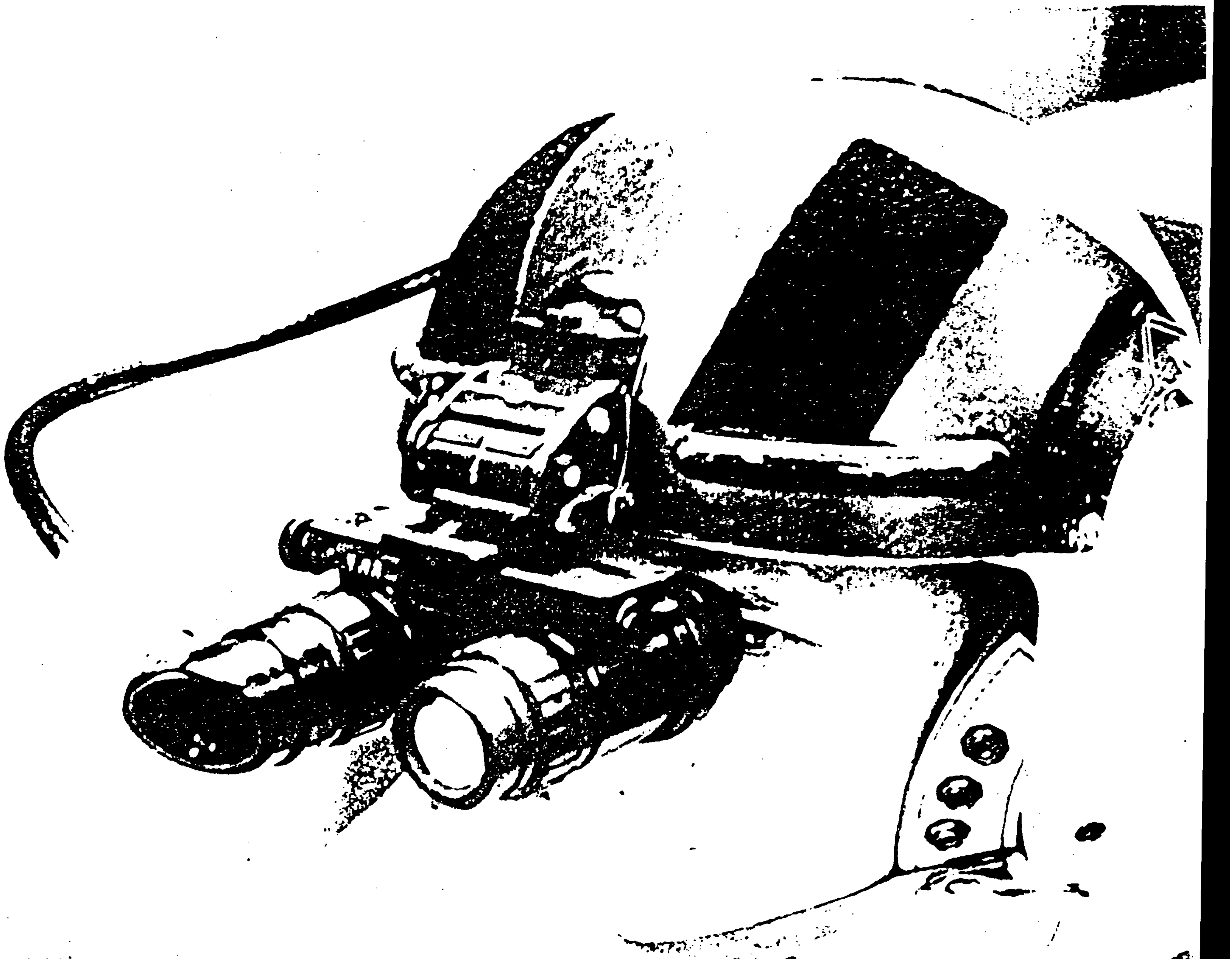
Night vision goggles (NVGs) considerations

The interest in night vision goggles (NVGs) for flying aircraft at night has increased considerably in the last several years. The NVGs are routinely used on some special operations aircraft such as fixed wing transport aircraft and helicopters (Fig 18). A key problem with using the NVGs in any aircraft is that they are not compatible with the incandescent lighting that is typical of aircraft cockpit illumination. The NVGs are sensitive to the near infra-red and the cockpit illumination emits a considerable amount of energy in this region. This results in considerable reflections in the windscreen making it virtually impossible to see out of the aircraft.

In order to reduce the glare and reflections caused by incompatible lighting, it is necessary to eliminate the infra-red portion of the cockpit lighting and reduce as much as possible visible light in the red and yellow regions of the spectrum. This can be done in several ways: using electroluminescent (EL) lighting, using light emitting diodes (LEDs), covering incandescent sources with IR blocking filters and turning off all unnecessary lights. These types of retro-fit corrections have been accomplished on a number of different aircraft including the Pave Low III helicopter (Fig 19), (Task & Griffin, 1982).

SUMMARY

It should be apparent from the information presented here that there are several aspects relating to "glare" and "reflections" that can have a significant impact on the pilot's visual acquistion of information which in turn affects his attitude awareness capability. Many of the problems discussed can be either eliminated or reduced in severity by using currently available technology and design techniques. The following references provide more detailed information on several of the topic areas discussed.



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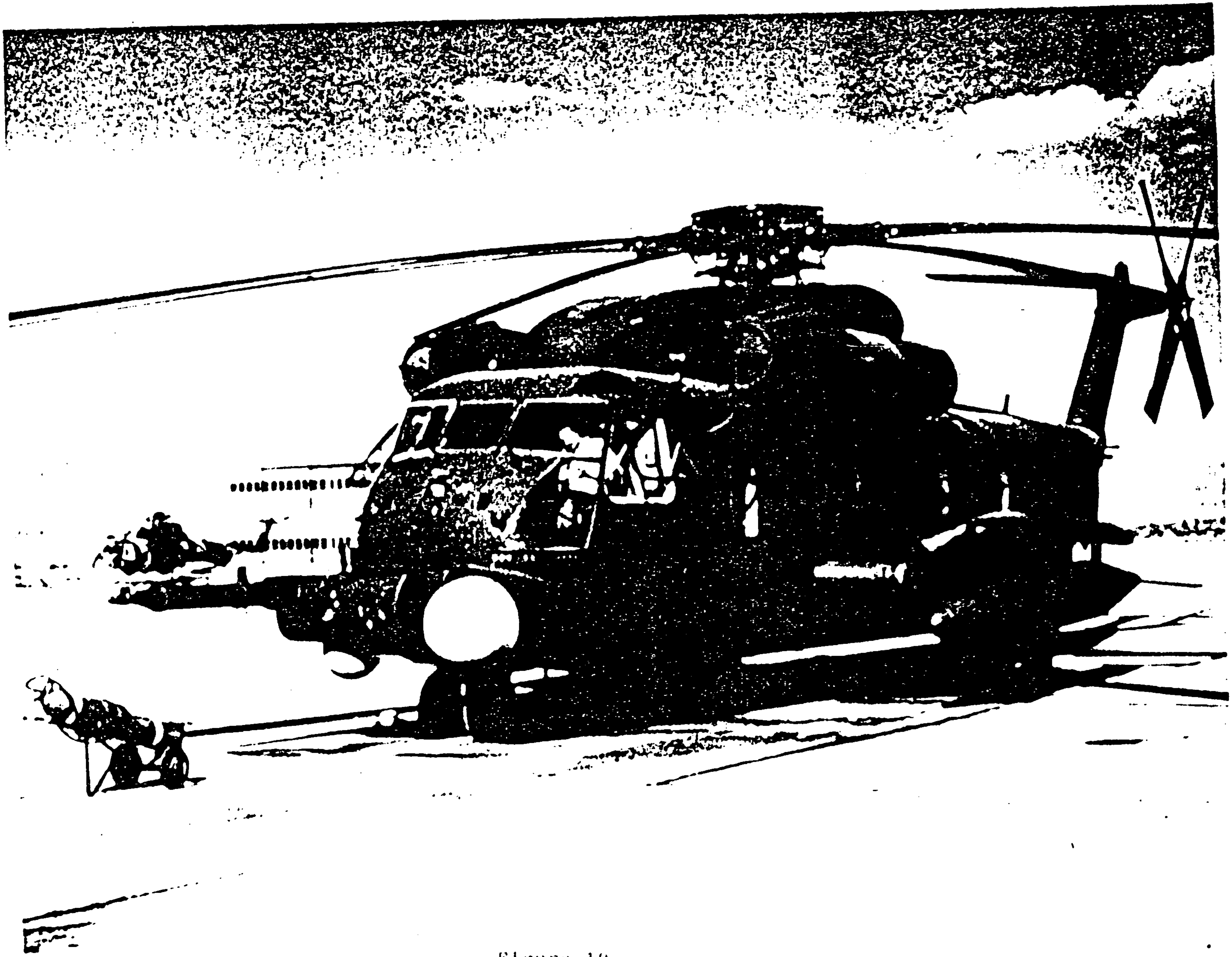

Figure 19

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COCKPIT WARNING SYSTEMS FOR LOW ALTITUDE FLIGHT

by

Capt Joe Byerly
3247 Test Squadron
Eglin AFB, FL 32542

BIOGRAPHY

- Originally from Vienna, Virginia.
- Attended the USAF Academy, graduating in 1976 with a B.S. in Physics and Mathematics.
- Graduated from pilot training in 1977 at Craig AFB, Alabama.
- Attended F-4 training at Luke AFB, Arizona.
- Spent two years (1978-1980) as an operational F-4C/D pilot at Torrejon AB, Spain.
- Transitioned to the A-10 at Davis-Monthan AFB, Arizona in 1980.
- Was a squadron instructor pilot in the A-10 at Myrtle Beach AFB, South Carolina for 2 1/2 years.
- Was a graduate student at the Massachussetts Institute of Technology, receiving the Masters Degree in Physics in 1984.
- Graduated in June 1985 from the USAF Test Pilot School at Edwards AFB, California.
- Presently working as the Director of A-10 Flight Test at the 3247 Test Squadron, Eglin AFB, Florida.

INTRODUCTION

The purpose of this presentation is to provide useful information for the design and implementation of future ground collision avoidance systems for tactical aircraft. Specifically, the differences will be highlighted between effective and ineffective cockpit warning systems for the single seat fighter pilot on low altitude missions. To limit the subject, the algorithms used in generating a ground collision warning will not be discussed. Instead, concentration will be given to the interface between the system and the pilot.

Additionally, tactical aircraft with a dedicated terrain following radar such as the F-111 and LANTIRN equipped F-16 won't be covered. Although some of the information will pertain to these aircraft, specialized missions such as night or in the weather low level flying are a subject all their own.

THREE PHASES OF LOW ALTITUDE FLIGHT

Limiting the subject to daylight good weather flight conditions does not eliminate the problem. Tragically, pilots do continue to fly perfectly flyable aircraft into the ground. To find out why, low level operations will be broken down into three distinct phases. this categorization was developed by Capt Milt Miller of the 162nd Air National Guard and A-7 Fighter Weapons School in Tucson as part of his Low Altitude Training program. The three phases are straight and level time, level turns, and vertical maneuvering. Each of these phases will be covered in some detail to discuss the pilot workload and inherent dangers of ground collision.

Strait and Level Phase

The straight and level time is the navigation phase of the low altitude mission. It is the time spent getting to and from the target area and makes up approximately 90% of the total time spent at low altitude.

The straight and level time is also the benign phase of low altitude flight because the pilot has time to make corrections to flight path deviations. Using the example of an A-10 at 300 knots and 150 feet above the ground, if the aircraft were to enter a one degree descent, an amount perceptible by the pilot, the pilot has over 18 seconds until ground impact. Even if the aircraft were an F-16 travelling at 480 knots, the one degree descent still allows over 10 seconds from 150 feet. Although these times may not sound like much, they allow the pilot time to take care of mission essential tasks which require looking other places than out the front. Examples of these are visual lookout, map reading, and miscellaneous cockpit tasks.

The visual lookout task involves an aggressive and systematic search pattern for air-to-air and surface-to-air threats. Full body movements are required to search the vulnerable areas at the aircraft's six o'clock. On combat missions, the visual lookout task is second only to avoiding the ground.

Even though most modern fighters display INS information in the HUD, the pilot still must spend a great deal of time map reading. Although the INS can be programmed on the ground, route diverts in the air are common due to weather, unanticipated threats, or mission tasking. Because these could come at any time the pilot is constantly updating his position on the map.

The miscellaneous cockpit tasks include all of the numerous items which require the pilot to look down into the cockpit. These occur throughout the low level mission and include radio and IFF changes, weapons switches, and INS and computer data entry.

To sum up the straight and level phase, the pilot is not always looking out the front of his aircraft because the mission demands that he look elsewhere, and he has time to do so. This is not true for the hard, level turn phase.

Hard, Level Turn Phase

The time spent making high g level turns is the most dangerous phase of low altitude flights. Although only five percent of the total time at low altitude is spent making hard, level turns, over 50% of all the fatalities from controlled flight into terrain accidents occur during these maneuvers.

The reason for the increased danger is the decreased reaction time available for pilot corrections to flight path deviations. This is illustrated by looking at an F-16 stabilized in a four g level turn at 480 knots and 150 feet above the ground. If the aircraft were to overbank by just ten degrees, the resultant change in the direction of lift would cause ground impact in 3.5 seconds. Even if the aircraft were an A-10 at 300 knots, the time available remains just 3.5 seconds. The ten degree overbank and resultant aircraft nose drop can be perceived and corrected by the pilot if he is looking through the HUD, but is can be easily missed if he is looking elsewhere. Capt Milt Miller is his Low Altitude Training briefing sums it up precisely by saying turning and looking is a death act!

The problem goes beyond the pilot's physiological inability to perceive changes in aircraft attitude. He establishes a habit pattern during the straight and level time of looking over his shoulder for threats and looking down into the cockpit for other tasks. If this habit pattern carries over and the pilot continues looking other than out the front during hard, level turns, the result can be fatal.

Vertical Maneuvering

The last distinct phase of low altitude flight is vertical maneuvering. This is the aggressive pull ups and pull downs where the pilot is either reacting to a threat or maneuvering to deliver weapons in the target area.

It is another high risk portion of the low altitude mission. Although vertical maneuvering comprises only three percent of the total time on low altitude missions, it accounts for one third of all the controlled flight into terrain aircrew fatalities.

The danger is due to the dynamic nature of the maneuvers. After pulling up from low altitude, the pilot is rapidly searching for his target, then making a high g pull down from a near inverted attitude to precisely align his aircraft for weapons delivery. If the pilot pulls for just a split second too long, he can find himself in a steeper than planned dive angle with not enough altitude to recover. Airspeed is another parameter the pilot must monitor because if he is too slow at the apex of the maneuver, the aircraft may not have the aerodynamic lift or "g available" to recover after the weapons delivery.

The well trained pilot can effectively employ his weapons and safely recover the aircraft in the target area by looking out the front of his aircraft. The HUD gives him important information such as airspeed and dive angle. More importantly, it is the visual cues provided by the aircraft's rapidly changing nose position against the terrain background which allows him to judge when he is getting in a dangerous position.

As with the hard, level turn phase, the pilot can only ensure his safety by looking out the front during the pull down portion of his vertical maneuvering. If he is distracted or habit patterns force him to look elsewhere, he may not perceive the rapid change in aircraft attitude. When he finally does look forward, he could easily find an unrecoverable situation.

REQUIREMENTS FOR AN EFFECTIVE GROUND COLLISION AVOIDANCE SYSTEM

After looking in detail at the low altitude mission and pilot workload during the three distinct phases, some common requirements for any effective ground collision avoidance system become obvious.

The primary requirement is for an audio warning. This has the obvious advantage of reaching the pilot regardless of where he is looking. The mission requires the pilot to look other places than the HUD while he is straight and level. During the level turn and vertical maneuvering phases, the pilot should be looking through the HUD, but it is the lapses in judgement when he looks elsewhere which get him is trouble. Therefore, a visual warning in the HUD is totally inadequate by itself. The audio warning is required to ensure the warning reaches the pilot.

Any audio ground collision avoidance warning must be clear and unambiguous to be effective. The pilot has to be able to perceive the warning above the other cockpit and headset noises without mistaking its meaning. With the numerous tones already generated by other aircraft systems such as radar warning, angle of attack, and gear warning, a human voice is the best option for getting through to the pilot. The actual words spoken are not that important as long as the meaning remains clear. Some effort should be made to standardize audio alert calls between different tactical aircraft with ground collision avoidance systems.

Two requirements on the algorithm itself are apparent from the discussion of the pilot workload on the low altitude mission. The first is that any effective warning system must have minimal false alarms. The system loses all of its effectiveness if the pilot has any hesistancy in believing it or reacting to its warnings.

The second requirement on the algorithm itself is the system must be effective at high bank angles. The radar altitude coverage should be accurate to at lease 150 degrees of bank, preferably up to a full 180 degrees of roll. As noted, it is the high bank angle maneuvers such as hard, level turns and those performed in the vertical maneuvering phase of low altitude flight which are the most dangerous, and therefore where the pilot needs the most protection.

SECONDARY WARNING SYSTEMS

Besides the primary warning generated by a ground collision avoidance system, secondary warnings are useful as either a backup or preliminary warning. For these purposes, visual warnings may be effectively used.

Examples of a visual backup warning is the flashing "break X" symbology in the HUD, which originated wit the A-7. This is still a viable warning, but it is only useful to the pilot when he is looking through the HUD. However, the pilot generally does not get in trouble when he is looking forward.

Perhaps more useful visual warnings are heads down cockpit messages which can serve as a preliminary alarm preceeding the primary audio warning. The latest software change to the A-7 ground collision avoidance system flashes the words "heads up" in both the INS panel display and TV monitor three seconds prior to the primary low altitude warning.

A final system which is particularly useful in training is a time that comes on at a pilot selectable altitude. This system would be totally separate from the primary ground collision alerting system which would have no pilot selectable features. The logic for the system would be the same as for the low light on most radar altimeters. That is, the time would activate one time once the aircraft descended below the preset altitude, and it would reset only when the aircraft climbed back above the reference altitude. This system is currently in use in Navy A-7 aircraft. The pilot selectable feature would allow the pilot his choice for altitude depending on his experience, the mission, weather, and a host of other variables. For example, a pilot new to the aircraft flying directly into the sun over rugged terrain might want to set the tone altitude at 500 feet, whereas the highly experienced pilot flying over flat terrain with the sun at his back might use 150 feet. Such a system would also be useful for flying instrument approaches, as a backup to decision height calls. It should be emphasized that this system could not act as a substitute for an effective ground collision avoidance system acting without pilot input.

SUMMARY

The pilot workload on low altitude missions places several requirements on any effective ground collision warning system. During the straight and level portion of the mission, it is reasonable to expect the pilot will be looking through the HUD less than 40% of the time as he takes care of other mission essential tasks. When the pilot is performing hard, level turns or vertical maneuvers at low altitude, he should be looking out the front, but distractions or habit patterns may force him to look elsewhere. This is by far the most dangerous aspect of the low level mission.

Therefore, the only truly effective warning is the clear, unambiguous audio warning that will reach the pilot no matter where he is looking. The warning system has to be effective at high bank angles with minimal false alarms.

Besides the primary audio warning, secondary visual alarms such as the flashing "break X" in the HUD or heads down cockpit selectable altitude can be particularly useful in training situations or when flying instrument approaches.

A well structured training program is the major part of the total solution to reducing the controlled flight into terrain accident rate. An effective ground collision avoidance system can help fill the gaps where pilot perception or judgement fail.

3-D SOUND IN WARNING AND ALERTS

Mr. Lewis Scott "Bo" Gehring
Bo Gehring Associates, Venice, California

INTRODUCTION (Col McNaughton)

One of the reasons we included this block on warnings and alerts is the fact that mishap records show numerous instances in which the pilot repeatedly ignored auditory warnings. Results include gear-up landings or getting too low on the glide-slope. When concentrating our full attention on some focal mode visual task, such as shooting an approach to minimums in a snow shower or in blowing fog, vision can tunnel, effectively shutting down peripheral vision was well as hearing. A problem with current warnings and alerts is that they are not always sufficiently commanding. Some, like the gear horn, habituate, and are psychologically tuned out. Others, like the low glide-slope calls, may simply lack the sense of urgency or immediacy necessary to interrupt one's consciousness. It seems that we all have about us a sort of psychological "sacred" space or bubble that must be violated in order to command our attention. This bubble may be violated in several ways: visually by a movement toward one's eyes, tactilely by a rap on the knuckles, or aurally by making a sound seem like it is coming practically from inside one's ear. Imagine the difficulty in ignoring a sultry whisper in your ear, or a rattlesnake in your ear.

BIOGRAPHY

The man you are about to hear, Mr. "Bo" Gehring, is a windsurfer, ex-sculptor, former professional motorcycle racer, private pilot, and engineering school dropout who has never stayed put in any school long enough to get a degree. He is also head of Bo Gehring Associates, one of the most successful companies in the highly competitive field of movie and TV graphics. Known throughout his industry as the "Image Maker," Bo is a major designer and producer of visual communications using the best of computer graphics art and design for what he describes as "synthetic picture making." It was he who created such films as the ground breaking ABC Logo introduced during the '84 Olympics, the Apple International commercial in which the multicolored apple wings through the channels of a computer clip and flows around buildings, and a shampoo commercial in which a blond emerges from a cube of rippling water suspended in midair. He worked on such films as 2010, creating the black monoliths that multiply and surround the planet Jupiter just before it is destroyed; and he generated special effects for films Star Trek and Nightmares. He is currently directing the industry's largest ever on-air graphics project for the Canadian Broadcasting Corporation. Bo has lectured in computer animation at many universities and was a speaker at the 1975 Aspen Design Conference. Bo responded to DARPA's request for help in producing an audiovisual display for the Pilot's Associate Project. It was while working this project that he conceived of developing some new ideas in aural communication which he calls 3-Dimensional Sound.

I'm used to doing pictorials so the idea of doing something you can't point at is a little new to me, but we'll try this. I'm going to play two tapes for you but I'll request a little faith. These were meant to be heard with headphones, not really with speakers. The audiences that have heard this agree that it's as compelling as actually being there. The first tape is a rough cut demonstrating my new, 3-dimensional sound process; it lasts 8-1/2 minutes. (The tape included a visit to the dentist's office for a filling, which led to the following remarks.) If you hear the tooth drilling with headsets, many can actually localize the tooth. What I'm trying to demonstrate is that you can localize sounds not only outside but also inside the head. When I first produced this, it caught me off guard because it was so compelling.

Regarding this sound, why is it so compelling? Now, I've worked computer graphics for years and I'm used to thinking in terms of high intensity, short time-live visual communication. I don't come from the university but I've worked in this daily for the past 12 years, so I think I know pretty much what there is to know about this and the power of this sound just totally surprised me.

Let me just talk about a couple of view graphs:

1. You can project into the listener's "sacred space" - about a 2 foot radius; there is a primal inability to ignore this. First of all, I've worked the entertainment industry 12 years and there is no communication medium other than sound that can invade this sacred space. It is well-documented that we have this two foot envelope around all of us, and if something gets inside it, we must attend to it, and if it's not friendly, we must deal with it. It's a very primal response that can't be ignored. Recalling when my kids were born, the first thing doctors test is a startle reaction, before the kids can see; and if they respond to a sharp instrument or a lot of noise, you know they've heard it. I've been trying to communicate very directly with people visually for years, and this exceeded anything I was able to do with pictures, so I started looking to find out why. The other part of it, which is a very technical thing that people in my industry have never picked up on, involves the artifacts of the way we record this material, that is, pictures and sound. The technology we have to record these two things is very different. If you think about it, consider an omni max camera, a show scanner, or any of the new, large format, high speed movie cameras. Calculating with your pencil, you can figure that they're recording only 5-10-20% of reality at most, and what they're

recording is a series of still images, which bear, I think, no direct relation to the metamorphic reality around us. That's because things don't move in 24th-of-a-second increments; they metamorphase, and presently we don't have any way to record that in vision. So it doesn't surprise me that they can't do good vision. I know because I've certainly tried to do a lot of it.

With sound, as it turns out, you get it all for free, because you can record in metamorphically.

Sound is a continuous medium. Pictures are incomplete by comparison; that is, we have no way to record reality visually or display it the way it really is. But with sound, you can record it metamorphically with even the simplest hi-fi, even these cheap tapes, and yet it's so powerful. You have all this hardware in the aircraft: your headsets are no doubt better than this little Sony Walkman; the delivery modem is already there. If you take the well-fitted USAF helmets that block outside noise and connect a unidirectional microphone at the top of your head, imagine trying to navigate with that. That's how pilots sense the aural world right now, because frankly, I think no one has noticed.

The thought occurred to me, why not make an auditory attitude indicator. Having survived a spin in a Cessna 150 on my second solo flight, I have some sympathy for the disoriented pilot for controlling things.

With regard to using it in the airplane, I've touched on the aspect of urgency. Another is that it's a parallel sense; it doesn't get in the way of things; it's a very primal sense and it's there all the time. We use it for navigating and for locating things, e.g., ringing telephone, chirping birds. Two unique attributes of 3-D sound are: (1) all around (4 Pi) sensing without the pilot having to move his head or interfering with other modes and (2) providing urgency as needed because close up "real" sounds can't be ignored.

The 4 Pi sensing comes for free and the resolution is excellent. The combination of 4 Pi sensing and the urgency could be used for RWR; a rattlesnake tone inside your ear could alert you and direct your attention to a particular spot in 4 Pi space, or to look at a display. I like the idea of a sound to cue you where to look, at a display or externally.

Let's play this second tape, a flight in an open cockpit biplane with an attitude beep overhead. (This was my first attempt to use a 3-D sound as an attitude indicator and is an example of how not to do it). As with the other cassettes, the sound source needs to be smaller. I got the idea of an aural attitude indicator that always indicates the direction overhead (or toward the Zenith) from my lawyer, who looked away momentarily while copying a clearance in IMC, and when he looked back, nothing made sense. When you're inverted, you'll hear the vertex indicator beneath your feet.

The other nice thing about sound is that it can be mixed. In vision, a huge amount of effort and money is spent in composing and organizing scenes to avoid occlusions or overlays. But in sound, you get it all for free. It can simply be added. It would be easy to imagiine a small electronic component with sufficient bubble memory that plays back some number of positions to allow the pilot to resolve his attitude. It would take information from the attitude indicator and pipe it into the headset.

With regard to aural attitude indicators, it doesn't matter where the pilot is looking. Sound can be modulated or brought closer to direct his attention to a developing problem via the intimacy aspect. If you're getting into some dangerous attitude, you want that sound to come up just like an electric drill inside you. Pilots have to participate in the decision as to what sound to use. This can be much more commanding/compelling/urgent than the voice commands that are "just out there." The technology should be available to create an aural attitude indicator. You can take a Sony laser disc and record, say, a hundred different sounds, and they could be very rich sounds, not just beeps, but a whole environment; you could record those on the disk and then use the attitude indicator to step it around. Record the sounds you want, store in bubble memory, then call whatever you want up as needed, and play it back digitally through the headset. This would provide a tool the pilot could use in real time. These are the other points regarding the attitude indicator:

- The technology is easy and can be used without other changes.
- Can bridge movements of visual inattention (e.g., looking away from the instrument scan, etc.).
- For less experienced aviators, an attitude tone could help maintain orientation. Could be simply a Polhemus Coil in a Sony headset.

Another application would be to design a sound environment in a virtual cockpit. If your attention needs to be directed to something, sound could do it. If he's got a threat coming from 6 o'clock, he should hear it. Some pilots like the rattlesnake idea, but it could be something else.

The environmental noise such as wind in the wires, engine and airframe noises are all but trivial. They provide significant orientation and situational awareness cues. And the technology is here to do it. There is so much going on in the sound synthesis literature that I don't have time to keep up with it.

There are waveforms that sound like concert instruments. I'm not up on military qualifications, but I can tell you that you can do it today.

The mixing process, because of the nature of sound, turns out to be painless--you get it all for free.

For this community, one of the best uses is localized communication with 3-D sound. Technically what's going on with this sound that makes it different is that it is spectrally shaped. A sound emitting object, such as a bird, can be located fairly accurately out in the environment; because of differences in phase and the shape of the frequency spectrum, the sound is slightly different in the two ears. That's why we hear the way we do. You can resolve that to fairly small angular acuities. It would be an obvious next step to localize it--e.g., to the control tower or your wingman, or to your adversary in an engagement. Sound would go through a little spectral shaper to modify the waveform. Gary Kendall of Illinois is pioneering work in this area. He's composing for entertainment things happening out in space. Tom Stockton, University of Utah, has synthesized Caruso's voice. The technology for this transient data, i.e., radio communications localized on the fly by microprocessor spectral shaping, or electromechanical devices, will require more research.

COMMENTS, Q AND A

Q: Localization should be possible using high frequency waveforms; e.g., ringing telephone or breaking glass. Do you have to look to localize sounds like those?

BG: No. What you are hearing is the spectral shaping performed by your ears as the sound goes in. What I have is a set of very good binaural microphones. Once the information is encoded, i.e., once the waveform is modified, it always sounds like it's coming from the same spot. Why it does so is another matter, but it sounds the same for all people even though all ears are not alike.

B/G Rufus DeHart: I am sure we can do this but is it practical? Most of our orientation cues come from vision ambient and focal modes. This will undoubtedly add cost to the aircraft. Is the increment improvement worth it?

Bo Gehring: If you could come up with a device that could be installed for about $1,000 per airplane, and it saved one aircraft per year, I would think it to be cost justified. I don't mean it to replace vision. This is an adjunct to vision. No reason, though, why it couldn't enable straight and level flying on aural references only.

Q: How do head movements affect the attitude indication?

Bo Gehring: A Polhemus Coil senses his head position and factors that in.

Q: When you generate attitude information, how do you generate pitch information? There doesn't seem to be enough phase shift or amplitude difference for minute pitch changes.

Bo Gehring: The waveform is different as it rises, as does the helicopter. Most people feel their hair move when the child whispers.

Lt Col Joe Bill Dryden: I'd like the localization to a threat but regarding a contiinuous attitude tone, I feel most guys would just tune that out right away because we're listening to other inputs.

Bo Gehring: You understand, this tape was done by a novice pilot who is not qualified to know what you'd want. It is technically possible to provide what you want based on research.

Dr. William Richardson: If we can design a warning system to keep him from hitting the ground, we're doing something very positive, and I think that's why we should push this.

Bo Gehring: With 3-D sound, it's possible to generate a horizon. I also did a little tape driving out here and it turns out, you also get a sound rush, like standing between two on-rushing trains. As you flew lower, it could provide that aural rush to complement the visual rush. A modular unit could play back one sound for attitude, another for ground rush. Remember, you can mix in sound.

Bo Gehring: The sound generator doesn't have to be too loud.

Bo Gehring: The wind-in-wires ambience can provide adequately useful cues.

Bart Brooks: I wish the headsets in the F-16's were as good as you suspect. They're just barely in mil spec for noise--the ECS is loud and already competes with noises you've got to hear, like RWR.

Col McNaughton: AAMRL is currently developing a noise cancelling headset useful for relatively steady-state background noise. Microphones in the headsets sample the noise, phase reverse, and play it back through the headset, effectively cancelling about 20 db. Should be available within 2-3 years.

Maj Art Fowler: The RWR rattlesnake tone cued you to check the RWR scope, and in SEA, provided a sense of urgency.

Bo Gehring: The design of Warnings and Alerts needs to be selective such that you don't clutter the environment needlessly, but you do get his attention when indicated. The secret is to let things make noise only when you need to think about them, and that's what I suggest.

Dr Richard Haines: Visual vection can create a sense of body motion. Is it possible to create that level of auditory vection?

Bo Gehring: I would like to see some research to find out.

Dr Haines: If you could, you might have a means of producing or preventing SDO or countering SDO.

Bo Gehring: Tom Furness has brought this up--that if you had a good strong audio environment, that if you know what reaches the pilot, whether it be an overhead beeper or wing lights or combinations, and you know he's disoriented, you could basically go in and get him. You might start with a sound which is referenced to him and then counter-rotate him into the airplane reference because you'd have the tool to do it with.

Bo Gehring: To me as a student pilot, it would have been great to have. I can't speak for the fighter pilots' problems.

AUTOMATIC RECOVERY SYSTEMS - TECHNOLOGY

Mr. J. Robert DeGiorgio
Lear Siegler Astronics Division, Santa Monica, CA

BIOGRAPHY

Mr. Robert DeGiorgio is employed by Lear-Siegler Astronics Division, Santa Monica, California. Bob has a degree in Political Science from California State University, Long Beach, California. He's a graduate of the Navy postgraduate school of Aviation Safety, Naval aviator; flew A-4's and 118 combat missions in Vietnam. He was an A-7 squadron commander; has about 300 traps; total military flying time is about 3,000 hours. He then flew with the airlines, Boeing 727's and the DC-10; he has about 10,000 hours. (He has almost as much time as our speaker last night, Jack Eggspuehler who has about 13,000 plus hours, 5,000 of which was instructing.) Bob DeGiorgio is presently involved in efforts to solve the problem of G-induced LOC in high performance fighters, and he's going to speak to us about automatic recovery systems primarily for incapacitated pilots....Bob!

The system that we're looking at is not a future system; it's current. We're in the process of trying to apply current technology, but one thing I would like to talk to initially, maybe get on my soapbox in the beginning here, is that we have been exposed to an awful lot of good information on attitude awareness, and we're talking a little bit about loss of consciousness now, and General Pruden the first day we were here spoke to some statistics that involved a certain amount of fatalities, certainly a large number of mishaps, and I guess what I would like to see come out of this is that as a result we march off and try to do something about it now that we're more aware of the problem. I talk now to the aviator in the room and we're among a group that certainly is not a hostile group when it comes to this problem; they're sympathetic, but out there in the procurement and acquisition area, not everyone is really sympathetic with where you would like to see the effort in dollars expended; that is to say that in the course of briefing and talking to the Air Force and industry, the folks in the procurement/acquisition process only have a finite number of dollars to spend, and if you want to see them spent in areas like solving the loss of consciousness problem, as an example, then it's incumbent upon each of us to march off and make sure that we are heard and hope that the dollars are spent and the lives are saved, and with no pun intended, but that we somehow positively make an impact on these statistics that we saw up here presented by General Pruden on the first day. We've gotta really do something; we've got to take some action.

Now, the first thing that I would like to show: we've talked a great deal about vestibular problems and ocular problems and what not. I participated in, in fact, kicked off a study dealing with the G-induced loss of consciousness problem and what happens with, in this case, one's hands.

Flaccidity is apparently implied when one lapses into unconsciousness in an airplane. We felt, initially that his hand would typically fall away from the flight control system, and I think that that probably will be proven out. But what I'd like to do is to kind of show you real quickly a tape on loss of consciousness incidents; this happened last week in the centrifuge. I want to talk about recovery systems, and what I will do is spin off on our efforts in the G-induced loss of consciousness area. But rest assured when one comes out of a loss of consciousness, G-induced in this case, let's assume he has all these vestibular problems and ocular problems that we talked about, what you're seeing here now is really a fatal accident from the pilot's vantage point (and let me go ahead and roll these). It's only a few seconds, but it will give you a kind of appreciation. Heart rate and g's are recorded. The g suit was not connected in this case. I went unconscious at about 8 g's and you'll see the incapacitation. I didn't experience a lot of the classic flailing all about the cockpit and what not, but we did have a stick force sensor in that cockpit and we were measuring the force applied to that stick, and it would indicate actually that the hand came off of the flight control system. So that's what got us into this auto-recovery effort that we're involved in right now.

Now again I say I'll spin off into some of the other things we've been talking about, but our effort was centered around the GLOC incapacitation. The functional incapacitation and reorientation period lasts for about 20-30 seconds in some cases in the old 42 year old airline pilots. If you weren't there last night, you won't get the gist of that, so in some cases the reorientation period lasts a bit longer, and for me, I didn't feel good for about two days. The Air Force conducted a GLOC survey some time ago; the Navy has, incidentally, also. In the Air Force survey (and these are right out of Air Force statistics from the Air Force Safety Center at Norton), they had about 1900 responses. There were 231 incidents reported. Sixty-eight percent of the GLOC incidents were reported to be the 4-7 g regime. Now what tactical airplane is incapable of that today? However, there are some tactical airplanes that are more capable of rapid onset of g and that's where the problem has surfaced; it's much more of a problem with an airplane that has the capability of rapid onset of g.

GLOC Accidents. Now these are in the 1983-84 time frame. Again, these are AF statistics: four F-16's (you can read it), 1 F-106, couple of F-5's, two A-10's; the F-20 accidents--the Northrop people are still trying to figure that out exactly what happened in those two accidents, but I believe that probably the first accident was not G-induced; the second one, I think, is highly likely. A recent MacDill accident (Art may know more about that). There's been some discussion that a most recent MacDill F-16 accident was also G-induced loss of consciousness. A T-37 in the fall of 1982. So we see the magnitude of the problem. Those accidents that you saw, have the implication of being observed by a wingman; that the profile was observed by a wingman, there was somebody there to observe the typical GLOC profile. Now, I asked how many accidents have we had over the years where there wasn't a wingman there to observe the profile and identify that as G-induced. Why now all the talk about GLOC? While GLOC has really always been a problem, we talked about it being in the 4-7 g regime. But with the dynamic instability that we now build into our airplanes in looking for great maneuverability, airplanes are much more capable of rapid onset of g; therefore, GLOC becomes more of a problem, with them capable of rapid onset of g, but, of course, capable certainly of high g first of all. High g load along with rapid onset capability. The GLOC initiatives that are underway now are physiological initiatives with weight training; frequent exposure to g is important - that increases your g tolerance so the more you're out there flying your jet and pulling g's, the greater your tolerance to withstand that.

Equipment. We talked briefly about the G-suit initiatives, now they're working on another thing at Brooks: assisted positive pressure breathing to increase g tolerance. We're educating our pilots now; all tactical aviators in the Air Force in the future will be required to go through centrifuge training. That will ultimately be done at Holloman, but until that centrifuge is up and running, we'll accommodate them down at Brooks.

Now the technical side: we're talking about auto-recovery. Now we're kind of spinning off into auto-recovery systems. There has been some discussion that further g-limiting would preclude GLOC from happening; if we further G-limit the airplane--that's unacceptable--we can't do that. Fred Hoerner yesterday talked to that. It's more acceptable to a tactical aviator to pull the wings off the airplane rather than be bagged by an Atoll missile, so he wants every g that you give him; every g that's available for that airplane he wants access to. So precluding GLOC by G-limiting is not the way to go; we don't further G-limit airplanes.

Auto-Recovery. Talking now about loss of consciousness in general, certainly GLOC is the problem that stimulated this solution. When a loss of consciousness is sensed, the flight control computer commands a wings level pitch to a positive rate of climb to a level off. I believe frankly in the positive rate of climb and probably leveling the aircraft off at some previously selected baro altitude. Given the environments in which we fly, the target areas, I don't think that the level-off is probably the way to go. I'd like to see some kind of positive rate of climb to a predetermined altitude at 14,000-15,000 feet, you level the guy off and put him in a smooth orbit and wait for him to come back to work.

An auto-recovery system can address a lot of things. It can address, of course, the GLOC; it can address loss of consciousness in general: cardiac; hypoxia; seizure; it can address spatial awareness problems; it can address auto-recovery systems; it can also address overload where a guy just says, "Hey, this is just too much for me"; and the unrecognized situation loss can also be addressed by an auto-recovery system.

Now the GLOC auto-recovery profile sensed by the flight control computer following a rapid onset of g: when the flight control computer first senses the rapid onset of g, it says, "Uh, oh, OK, hoop one has been jumped through; rapid onset of g, now let's watch and see what happens." The thing that we're kind of looking at now would be followed by lack of stick force or purposeful contact over a period of time. The time constant that we're looking at, we're giving an option here, above let's just say an arbitrary figure, above 10,000 feet maybe you'll give the guy, maybe it's 15,000 feet, whatever, you'll give the guy 5 seconds off with the lack of stick force input following the rapid onset of g or lack of contact on the stick for maybe a period of 5 seconds; but below 10,000 feet at the lower given altitude, you can start marking off these times and shorten them. In other words, the closer you get to the ground, the less time we would allow him to be off the controller before we start flying an auto-recovery profile.

Cardiac, hypoxia, seizure sensed by lack of stick force or contact over a period of time. The g is out of the picture here so in your flight control computer, you can have in the algorithm, a logic that says "okay, g hasn't been rapidly onset, but this guy's been off of the flight control computer for 15 seconds or whatever. Now we're talking about when he is not in an autopilot mode, he's hand flying the airplane, so there are things that we can do with this, too.

Now there is also a crisis switch. I'd call it a crisis switch; a guy's having a physiological problem, he's having a medical problem, he doesn't want to reach down, or can't, or whatever, or he needs quick access to a recovery system of sorts and rather than engaging the autopilot, he can hit a bang switch, and the aircraft will either fly a profile for him, or level the wings. In fact, the spatial disorientation or overload the pilot or wingman recognized, the pilot is still with us; he is not unconscious, but he has lost control of the situation; he recognizes he's disoriented, or the wingman recognizes that he's disoriented and announces it to him. Says, "Hey, you've got a problem, I think you've got vertigo." In fact, I have had that happen where a wingman was out there and he was drifting back and forth; we got to talking about it; he just didn't know where he was, and again the crisis switch. Now this crisis switch is actually happening in the Lavi (Israeli Fighter). We do the flight control system for the Lavi--it's a triplex digital flight control system and they spec'd in that flight control computer exactly this--a mash type crisis switch--when it gets to be too much for the guy, overload or whatever, spatially disoriented, he lunges and bangs the switch and the aircraft flies a profile or a wing leveler.

Unrecognized situation loss: Well there is a prototype computer out right now that picks out the number of sensor inputs and can recognize emergency situations and displays corrective action to the pilot so that they are applying now artificial intelligence; it displays the corrective action to the pilot, and if he doesn't take corrective action, then it takes it for him. That technology is here now.

Now a spin-off to that technology is what I would call, and we are looking at this, a parameter management system. I've just taken an example here of how such a system might work. I've taken a pop-up roll ahead, a weapons delivery profile. The system would be programmed by the pilot on the ground, on the carrier, prior to launch. He programs any number of his systems; he programs his parameter management computer, dials in, "Well, I'm going to go air to ground". We may dial in a number of missions: Air to ground, plugs in air-to-ground; I'm gonna go weapons delivery, plugs in weapons delivery; and the specific weapons delivery that I'm going to fly, the specific profile: Pop-up/roll ahead - boom, he bangs in PURA. Now PURA for this would be a typical profile here; this happens to apply pretty much to the A-7, but whatever that PURA profile is, it's known to the computer for that airplane--500 kt run-in, as an example, 200 feet altitude. You'd pop-up at 15,000 feet, you pull 4 g's. We didn't put this on here, but you roll out, you come up over the top at about 4-5,000 ft AGL and you deliver the weapon in about a 10o dive; you drop the weapon at about 800 ft, so you're out at about 500 ft. The computer knows this, the computer knows what the typical parameter is. So if the pilot breaks any one of these parameters, then you'd have a discrete display in the HUD, maybe an audio as well, that would read out "altitude, altitude," "airspeed, airspeed." This is just an example: "g's, g's." Now again these are all picked off of existing sensors in the airplane.

Here is the range marker. We've run-in, we've overshot the 15,000 foot marker, we're now at 13,000 feet; we apply the 4 g's on the airplane, should be downhill, we still roll out at 4-5,000 ft, but because we busted this parameter, we're 2,000 ft closer to the target, we've got a much higher dive angle now, and if we try to deliver that weapon at 800 feet, we may impact the ground with the airplane. The pop-up roll ahead happens to be a delivery that you're likely to run into problems like this were you to bust some of these parameters, some of them are more critical than others. Again, a parameter management system for this particular delivery could enable you to do this with a 45o angle dive, a medium angle dive. I mean, any number of weapons delivery systems can be plugged into this computer and give you a how goes it, a discrete when you're not meeting the parameters.

Now, something we've also kicked around and discussed is in the bombing computer. An A-7 bombing computer, as an example, the CP-741 has a break light, the F-16 has a break X-light. There are things we can do here also, and we've been kicking these around as well; the break X-light illuminates, that means you've gotta pull 4 g's within 2 seconds and establish that profile and maintain it or the aircraft is likely to hit the ground. Most guys see the break X-light once in their lifetime, I guess. So what we do is we say all right, the break X-light illuminates. We put the g on the airplane (if he doesn't put 4 g's on the airplane, he's likely to hit the ground), so we'll give you whatever g is required to keep from hitting the ground. Again, we're talking about auto-recovery or auto-assisted g program in this case. Now if the guy usually flies close to the limit, then maybe we wait until the computer recognizes that now he is going to require about a 6 g profile to keep from hitting the ground, and that's what we give him, 6 g's. Now we started talking about a parameter management system. Just observing and watching the scenario unfold, what is implied here might be an auto-recovery. I won't go so far as to suggest that in this particular case, but when these parameters are broken, will we consider taking control of the airplane? I can't bring myself to that yet, but that might be implied.

Industry and DOD Effort: We're working on the auto-recovery system for G-induced loss of consciousness. We've heard from GD and their AFTI efforts. GD is also working on the auto-recovery system for GLOC. In fact, that system is now to the point that there is a statement of work out, so we are working an auto-recovery system for the F-16 for G-induced loss of consciousness, retrofittable to the analog system. Northrop is concerned about the F-20 problem--they're working it. Centrifuge studies are underway. The Air Force is leading the way in this particular, i.e., in the area of GLOC. The Navy is coming along now and expressed an awful lot of interest with the problems implied in the F-18 as well. So that's my presentation, and are there any questions? Yes sir!

Q: In combat would you be inclined to level off, because he's gonna get shot down?

JRD: Well, there's no denying he runs a risk of being shot down, but the Pk of any weapon is less than one. The Pk of the ground is one.

Q: This seems like a bandaid. If I were to put money into a cockpit, I'd put it into cockpits that kept the pilot from losing consciousness.

JRD: Well, we kicked that around, talked about that at breaks with a couple of folks, and we believe that the airplane is always going to stay ahead of the pilot in terms of the physiology of it. The man is never going to be able to be capable of pulling the g-loading; we're looking at 12 g airplanes now, and man is never going to be able to keep up with that kind of g loading.

Visitor: I don't agree with that at all because I think we can design a cockpit where the pilot can stay conscious under any kind of g you put on him. However, if you put the fairly heavy g's on it, you're going to have to beef up the airframe to the extent that to keep the airplane from falling out of the sky, it would take 100,000 pounds. I think if we design it right, you can have a cockpit as well as airplane that one can survive.

JRD: Now, we've discussed this with a lot of fighter pilots with TAC and again, let me back up to Fred Hoerner's comment, "What is the alternative?" You know, in a combat situation, I had one pilot say, "Hey, that's real good for a training environment, but I wouldn't use it in combat." On the contrary, I would use it in combat because what is the alternative? And we are talking about the GLOC situation here now, again GLOC. Rapid onset of g because a missile is in the air knocks the pilot out, he finds himself unconscious, well he still has the opportunity to wake up, and the fact of the matter is, that missile may not track, and if you would look back at our Vietnam experience, it may fall off like a bomb when the guy punches it off the airplane, so I don't see what the alternative is.

Visitor: I agree with the initial premise tabled that perhaps something would be good to take over if the pilot has been shot or he has lost consciousness due to g. But, it's what happens after that that I disagree with this particular methodology.

JRD: The profile, you mean?

Visitor: I would like to second one observation that Al made about the fact that cockpits can be designed to increase g power. Many of you may know Hiram Bombet, Dr. Bombet at Warminster NADC, and he told me that he flew on the centrifuge and was able to pull 13 g's.

Q: For how long?

A: For about 15 seconds, I think, if I remember correctly, but if anyone can probe that study, Dr. Bombet says we may pull as high as 26 g's in a study done for the Air Force as a matter of fact.

Visitor: If you distribute your load, you can. You understand, it was in a contoured couch and he was tilted back supine.

Joe Bill Dryden: If you tilt him back, he can't see anything. There's a tradeoff.

Q: If you accept as top importance the pilot's mental capability in the airplane, then you have to make compromises in order to keep being conscious, and if he's unconscious, he's not an effective operator within the weapon system, so do we buy the consciousness or not?

MAJ Art Fowler: You know, that G is hard on you. I used to be 6'5" and now I'm 5'6". Pulling G is very fatiguing, it wears you down. I don't want to have to go out and pull 9 to 12 G. I'd like to be able to do it with only 4 or 5.

Dr. Richardson: You can't revoke the laws of physics.

Frank Watler: He's got a very good point, like looking at performance profile for the quickest turn. Generally when you're pulling g, you want to change your direction, okay? Now, if you do it efficiently and properly, there's a g above which you begin to lose energy, and I think his point is well-taken that we need to blend the software and performance characteristics of airplanes in that particular envelope so you fly them more efficiently.

JRD: The task at hand here was trying to solve the g-induced loss of consciousness problem, and right now, the capabilities of the airplane exceed the capabilities of the pilot.

Q: I wonder why there were no F-15's in there. Maybe we ought to look at the stick in the center and the possibility of over g-ing the jet, slowing down the g-onset range; vs the F-16, where the pilot can whip back and go instantly to 9 g's and never have to worry about over g-ing the F-16.

JRD: We're talking about accidents. There were no F-15 accidents reported, but I can show you a survey with an appreciable number, a very large number of F-15 incidents where guys reported, "Yes I was knocked out with GLOC."

Dr. McNaughton: Gentlemen, we're running out of time right now, but we have had many F-15 GLOC's reported; and there have been a couple of F-15 mishaps that were essentially unexplained, but, when looked at carefully, could have been due to GLOC. I would also reiterate Bob's point on the pervasive value of an auto-recovery system: pilot incapacitation from whatever cause:

> Physiological: Hypoxia - we lost an F-15 pilot several years from this.
>
> Medical: Cardiac Event - lost an A-10 pilot last year from a heart attack. Seizure - a T-37 IP had a Grand Mal convulsion in-flight; the SP recovered the aircraft; diagnosis - brain tumor.
>
> Visual: from flash blindness of lasers or nukes; the Soviets are known to be proliferating battlefield lasers capable of flash blinding pilots.
>
> Severe Incapacitating Vertigo: what's wrong with letting go of the controls say, "You got it GD/Sunstrand/whoever," and let the plane auto-recover?
>
> Or, with the state of the art in Terrain Following/Terrain Avoidance, could we not have the auto-recovered aircraft in the combat environment simply TF/TA its way home until the pilot recovers?

MAGIC OVERVIEW

John Reising, Ph.D.
AFWAL/FIGRB, Wright-Patterson Air Force Base, Ohio

BIOGRAPHY

John Reising is an Engineering Psychologist at the Air Force's Flight Dynamics Laboratory located at Wright-Patterson Air Force Base, Ohio. After receiving his Ph.D. in Industrial Psychology from Southern Illinois University in 1969, Dr. Reising joined the Bunker-Ramo Corporation where he worked as a Human Factors specialist. His primary work efforts centered around the design of advanced cockpits and the execution of experiments to investigate new control and display concepts.

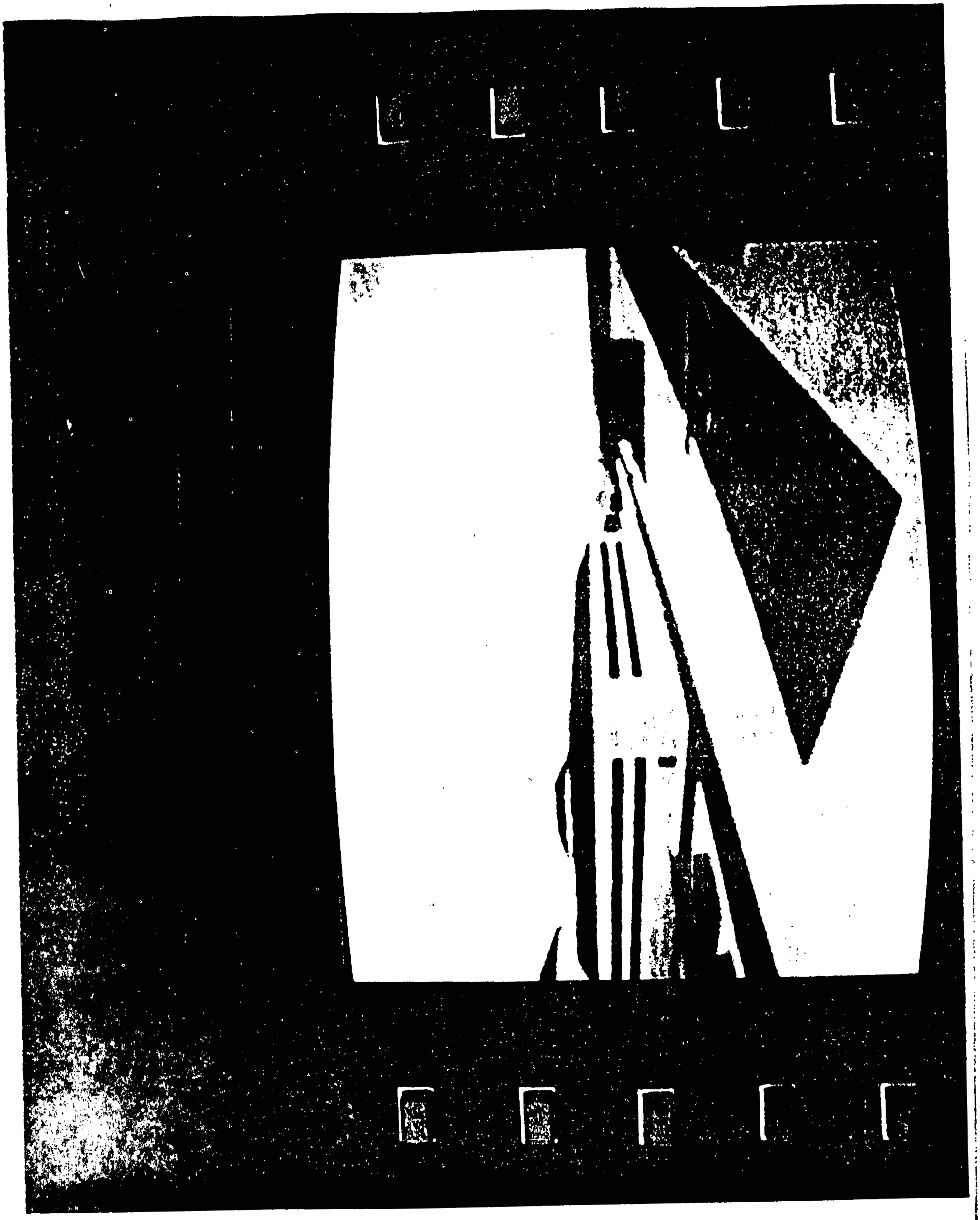
In 1972, he left Bunker-Ramo to join the Flight Dynamics Laboratory where he is at present. His current research still centers around advanced cockpit design, with a special emphasis on blending the many new cockpit technologies so that the pilot can use them optimally. Currently under examination are color cathode ray tubes, flat panel displays, touch sensitive overlays, voice control, and programmable switches. He is also studying Artificial Intelligence concepts as a means of reducing the pilot's information processing load.

Good morning! I'm going to talk a little bit about MAGIC, the acronym for Microprocessor Application of Graphics and Interactive Communications. What I really want to concentrate on for this conference is the use of graphics and displays which I think might be able to prevent some of the situations which get you into unusual attitudes.

This is an example of our cockpit (Picture 1). It has five color CRTs; it's a distributed microprocessor based system and is very flexible. If you look at this middle display, we have programmed up a format in which you can watch yourself fly up the hills and valleys. Now this is not a flight display, I want to stress that -- you don't fly by this display. This is a situation display much like an HSI would be in the old days. You watch yourself fly; it's a perspective view, a look ahead view, and you can rotate the viewpoint around your airplane. It's an outside-in display -- your airplane flies, the world stays still, just like an HSI.

This other display I want to show you is a computer graphics generated picture, in our case, of a target area (Picture 2). Now the key thing about it is that it's in a data base, and it will be real time. Don't forget we're in a laboratory. Because it's in a data base, it's not like a videotape. It'll respond and it's a computer generated picture, and as you fly and roll

Picture 1



Picture 2

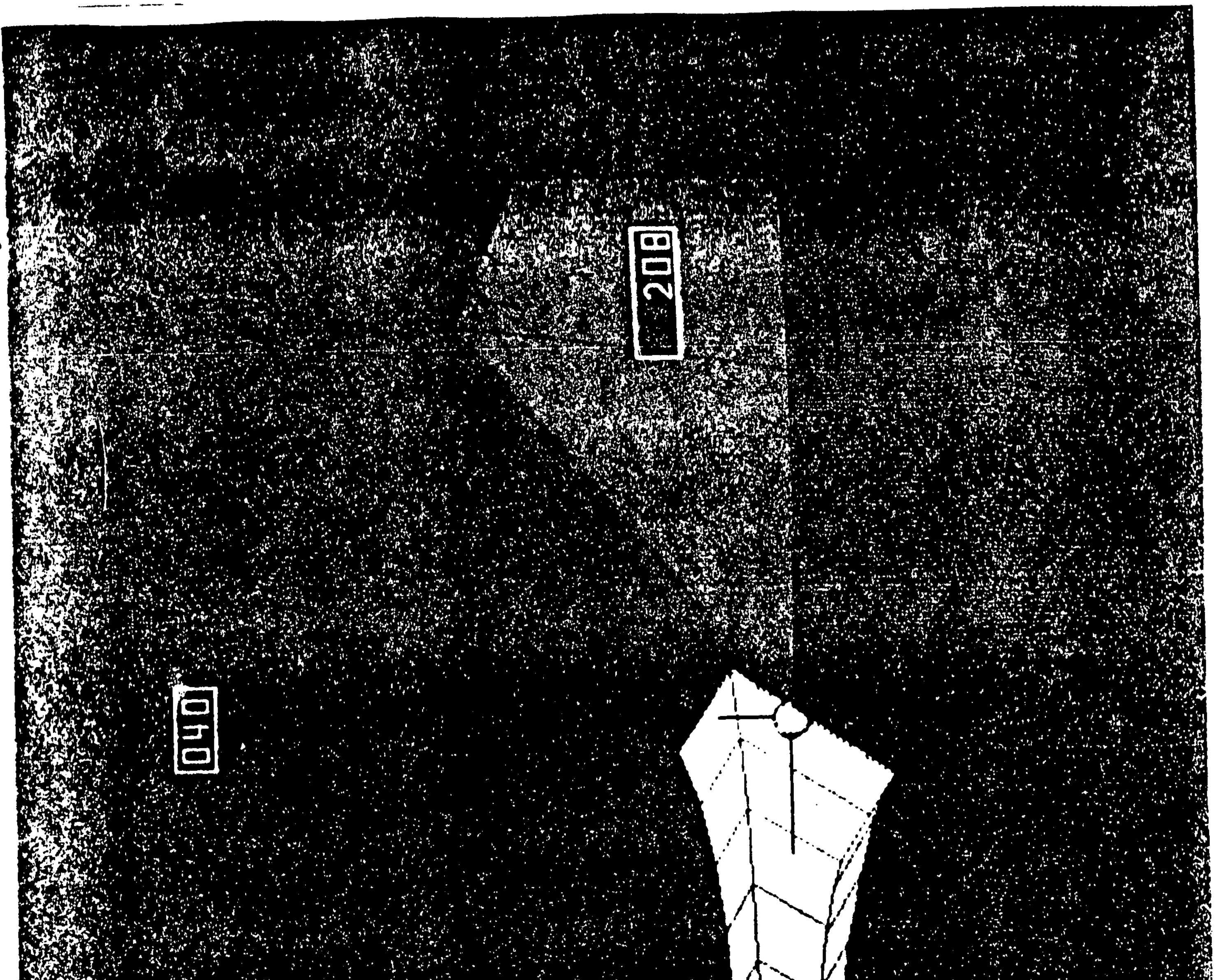
and go upside-down, so will the world. This is a close in view, and when you're flying a pop-up ahead, you could actually have this picture come up and you could see the profile, practice the profile on the ground, and take a preliminary look at the target while you're cruising to it. You could practice delivery runs, you could see what things look like, and you could annotate parameters on this kind of display.

Here is an example of the kind of cockpit display we see in the future where we'll eventually have color on a HUD (Picture 3). Instead of just having FLIR on the HUD, we've given you a color picture on the HUD, a flight path in the sky. Picture 4 shows a look-down view like you would have on a current map, all computer generated. It's not just something we drew up with an artist's conception; this is the display we flew at Boeing, where 30 Air Force and Navy pilots flew our advanced cockpit.

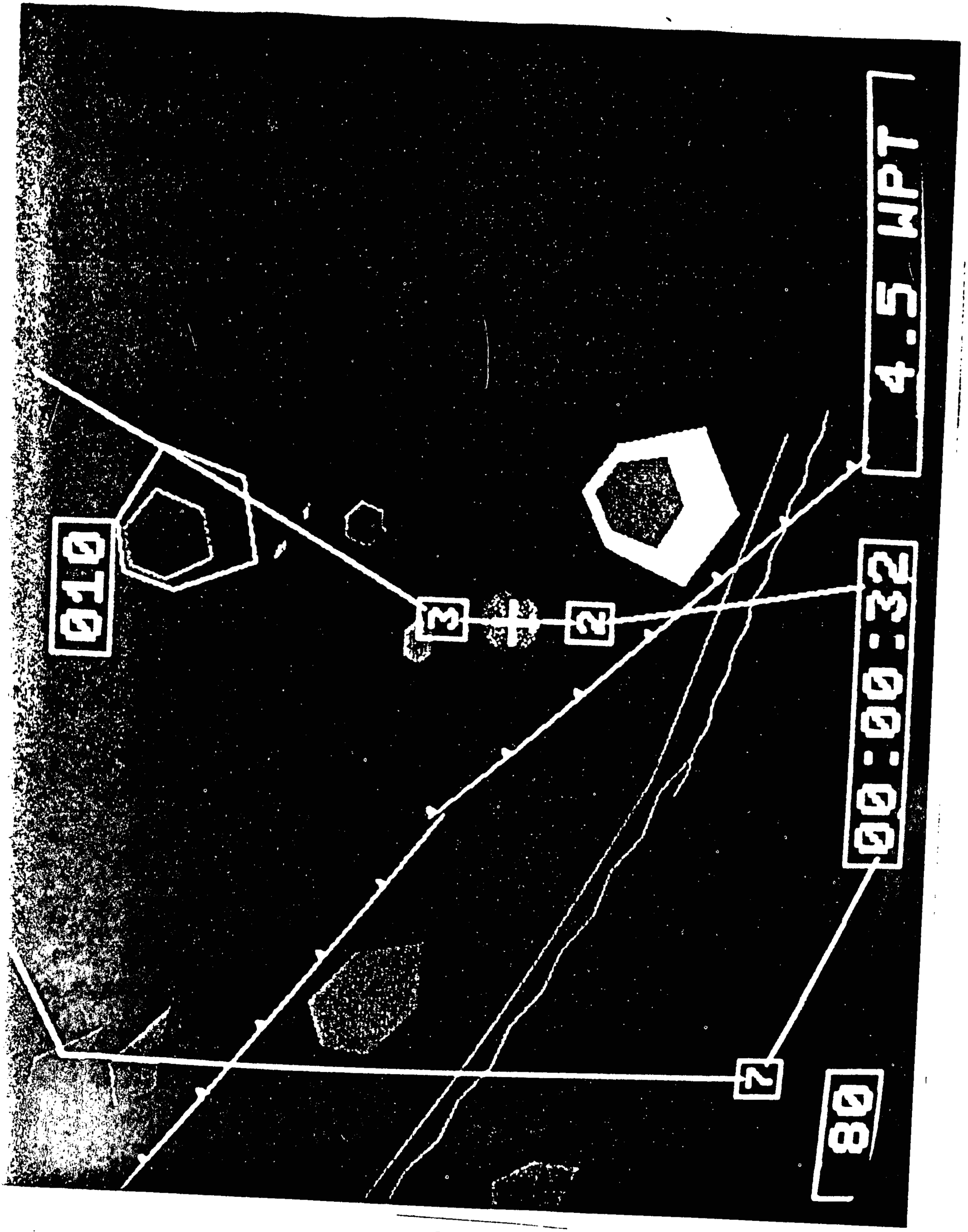
At this particular time we're using a channel in the sky as the primary flight instrument. Here's a case where we used a low resolution CRT as you can see, but we colored the channel a different color on the outside (Picture 5). Now whether it has to be orange or not is incidental, it just was another color, but you can see you always want to fly up and get back in the channel. The channel never goes away. No matter what your attitude is, it will never disappear, so at least you always have a recovery point. If you're looking down at the road surface as it were, we color that differently (put green stripes on it), so you know where you are (Picture 6).

This is the other conception of that perspective, the look ahead display (Picture 7). When we actually flew this at Boeing, we chose a default point; you were 5,000 ft back and a 1,000 ft above your own airplane. We didn't have the computer power to give you the ability to adjust that constantly. This is your track as is generated by a tactical flight management system. These are the probability of kill zones for surface to air missiles, and the probability of kill zones for a tracked gun like a ZSU-23; these are the probability of kill zones that were stated by Intell but this SAM is not active. This SAM is actually tracking you; he's off the screen and that little orange circle indicates your ECM's effective. The key thing that I wanted to show you though is that you're watching yourself; these are hills you might run into, the green indicates terrain that's below your current flight altitude. So what I have done, I've got inside-out and outside-in views on two separate displays. Referring back to Picture 1, this is a picture of the HUD, the perspective view and the map. There was zero confusion having an inside-out and an outside-in display because they are situation displays; not a flight displays. We had 30 Air Force and Navy pilots who had no problem whatsoever with any confusion. Although this was not an unusual attitude recovery study, they did feel that this gave them very good situational awareness, these two displays, and, of course, always knowing where they were on that flight display also helped.

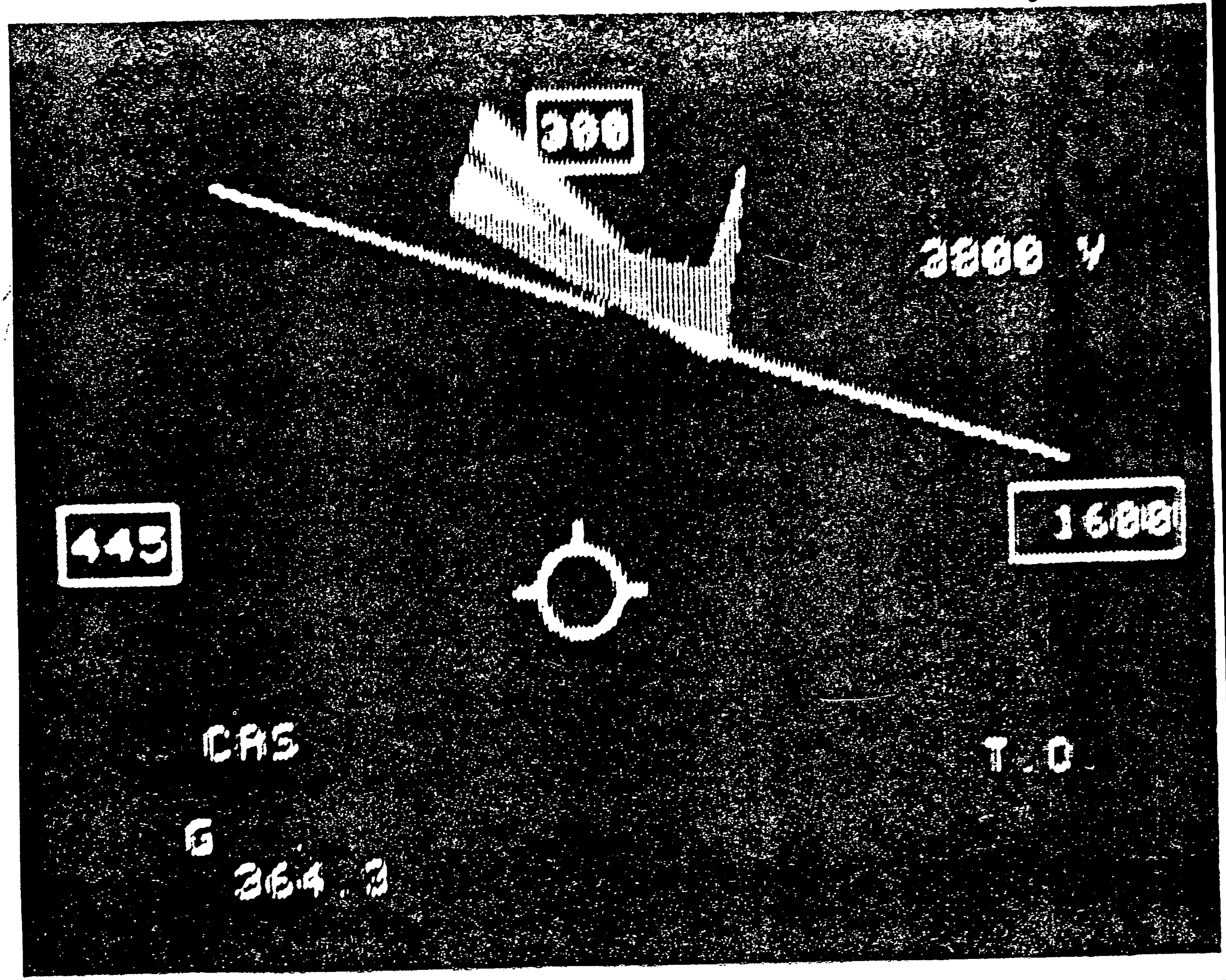
Now, since we did this, I had an opportunity to go to NADC and fly their simulator, and they have a pathway in the sky. It's not crucial whether we



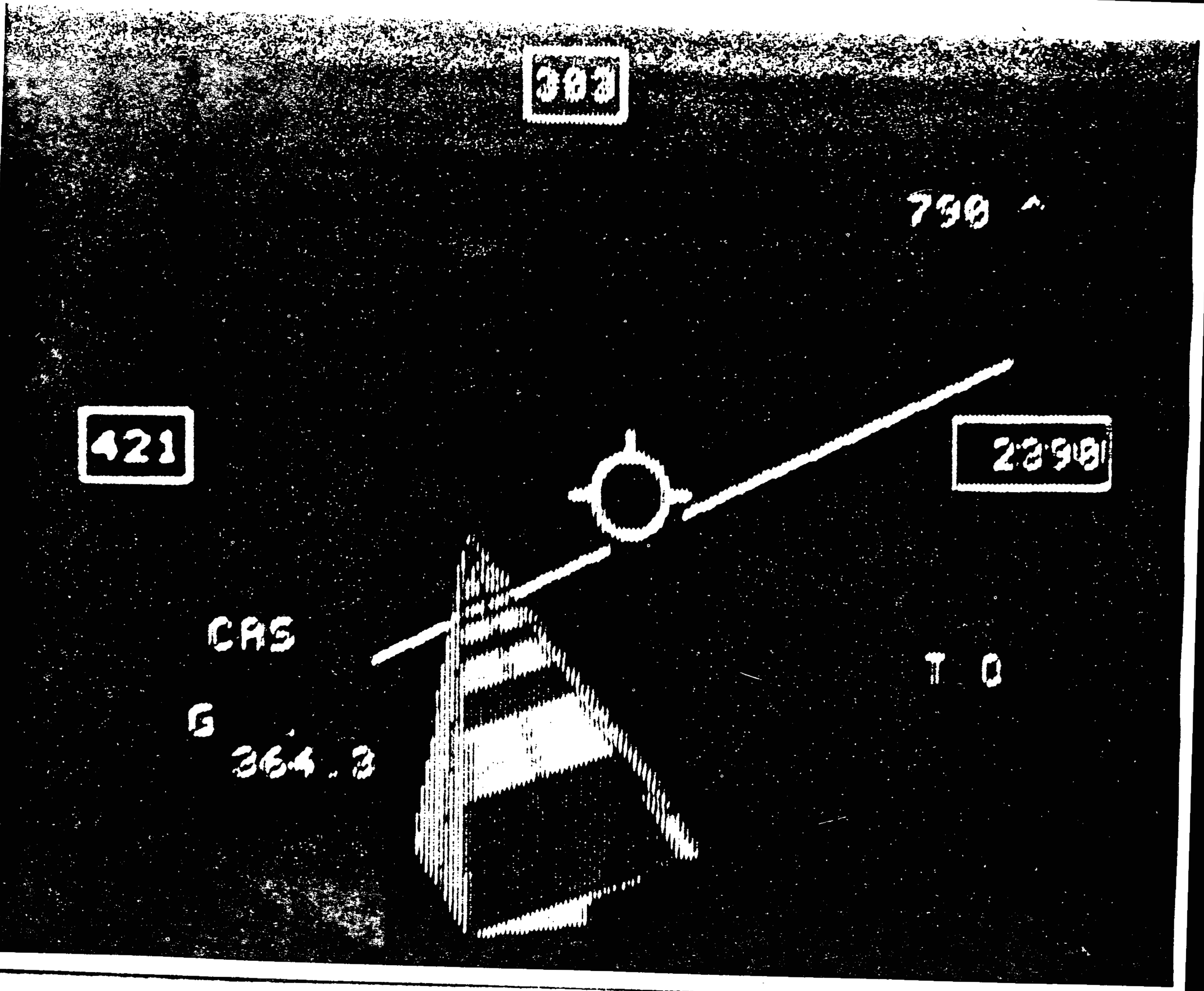
Picture 3



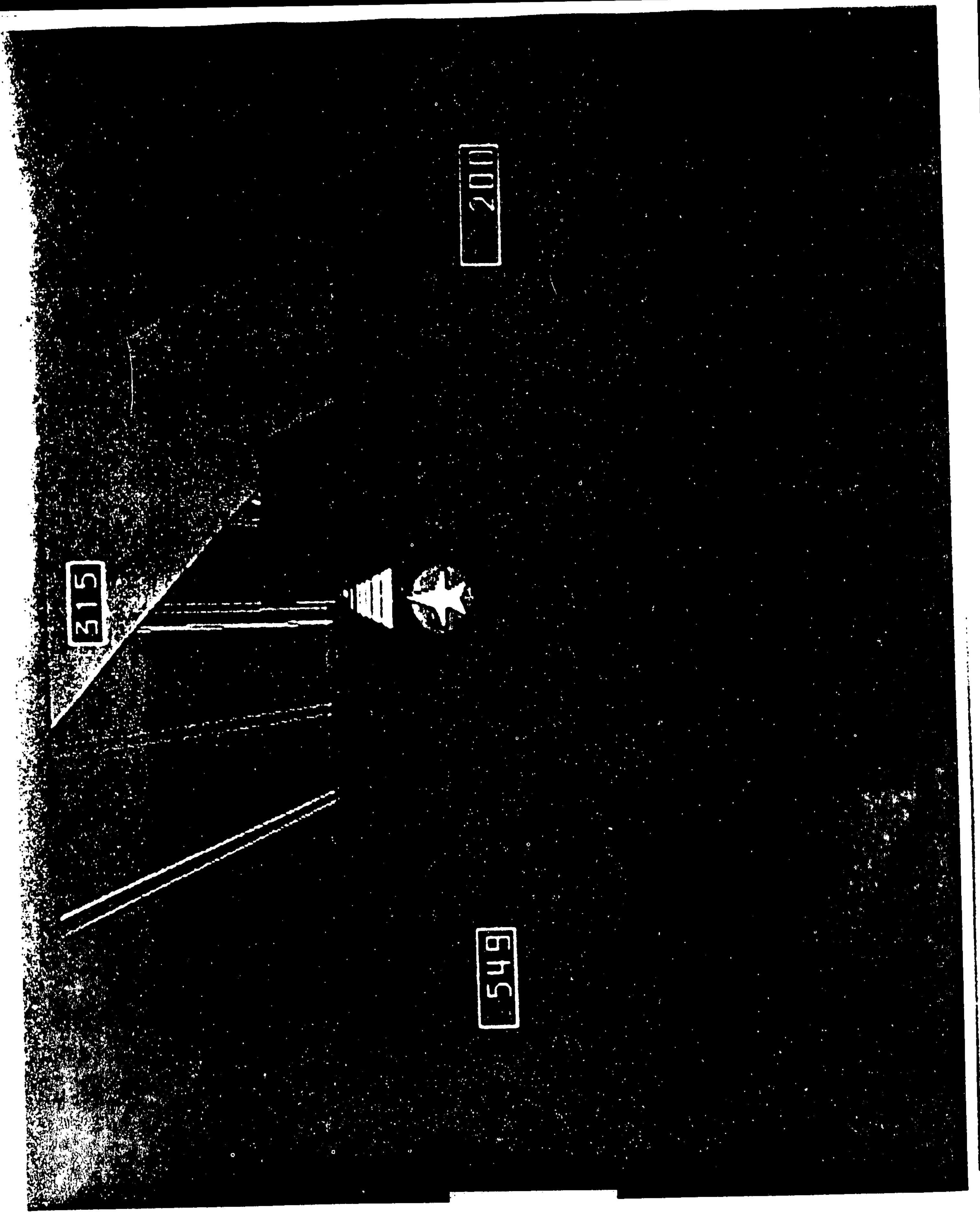
Picture 4



Picture 5



Picture 6



Picture 7

use the channel or pathway, sometimes NASA uses a tunnel -- they put a roof on the channel. The key thing is maintaining proper attitude control. Since I've flown the NADC simulator, I think we're going to go to a pathway. But, there's the thing I wanted to point out about it; since I'm not a very good flyer at all, I didn't try to put myself into unusual attitudes, I just got there. But I found that I could recover very easily with the pathway in the sky at the NADC simulator, so it certainly convinced me.

The latest thing we're doing is putting out a Request for Proposal now to look at 3-dimensional views, genuine sterographic views of the perspective view and flight path displays, to see if the 3-D gives you some more help in situational awareness. That completes my presentation. Are there any questions?

Q: John, if you're behind your airplane, if you see your airplane going into the ground, will you bail out?

A: I hope that when you see that, we'd have the auto-recovery system to help you along.

VIRTUAL COCKPIT CONCEPTS

PROBLEMS WITH PRESENT COCKPITS

- TOO MANY CONTROLS/DISPLAYS
- INFORMATION HIGHLY CODED
- INFORMATION NOT WHERE NEEDED
- LOW BANDWIDTH CONTROLS
- LACK OF "SITUATION AWARENESS"

WAYS TO IMPROVE COCKPITS

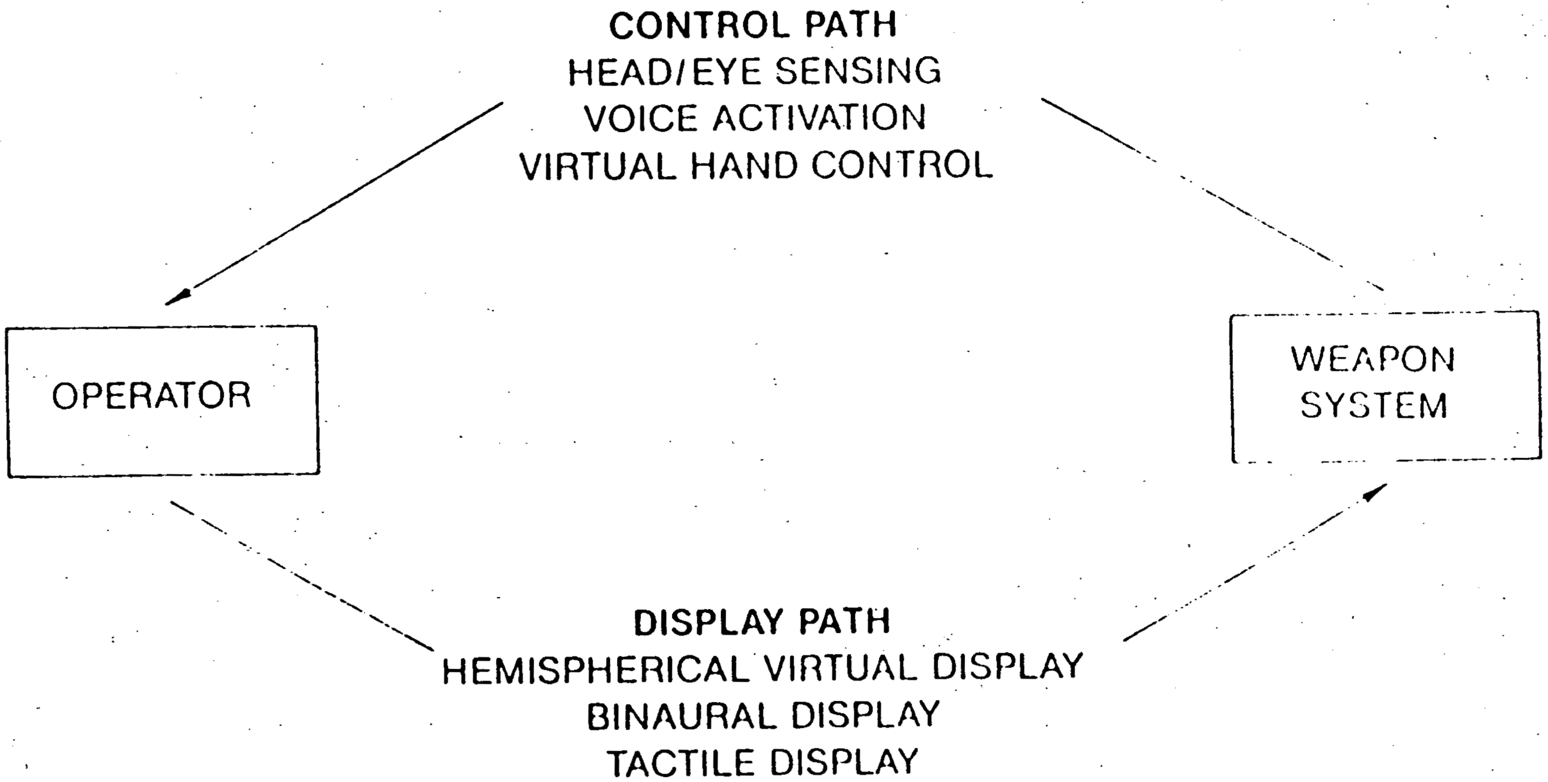
- INFORMATION ORGANIZATION AND PORTRAYAL
  - ELIMINATE HIGHLY CODED INFORMATION
  - ORGANIZE INFORMATION "SPATIALLY"
  - USE PICTORIAL REPRESENTATION
  - SCREEN/LIMIT/SELECT INFORMATION AUTOMATICALLY
- "HIGH BANDWIDTH" CONTROL INTERFACES
  - USE **NATURAL** PSYCHOMOTOR CONTROL INPUTS HEAD/EYE/HAND/VOICE
- AUTOMATION
  - NOT TO MAKE **EASY** BUT TO MAKE **USEFUL**

VIRTUAL COCKPIT

A DEFINITION...

INTERACTIVE SYSTEM WHICH ORGANIZES AND REPRESENTS BOTH SPATIALLY AND TEMPORALLY ALL COCKPIT INFORMATION IN THREE-DIMENSIONAL VIRTUAL SPACE IN ORDER TO COMMUNICATE AN OVERALL AWARENESS OF AND TO PROVIDE THE CONTROL OF WEAPON SYSTEM STATE RELATIVE TO THE WORLD, IT'S THREATS, AND TARGETS.

VIRTUAL COCKPIT



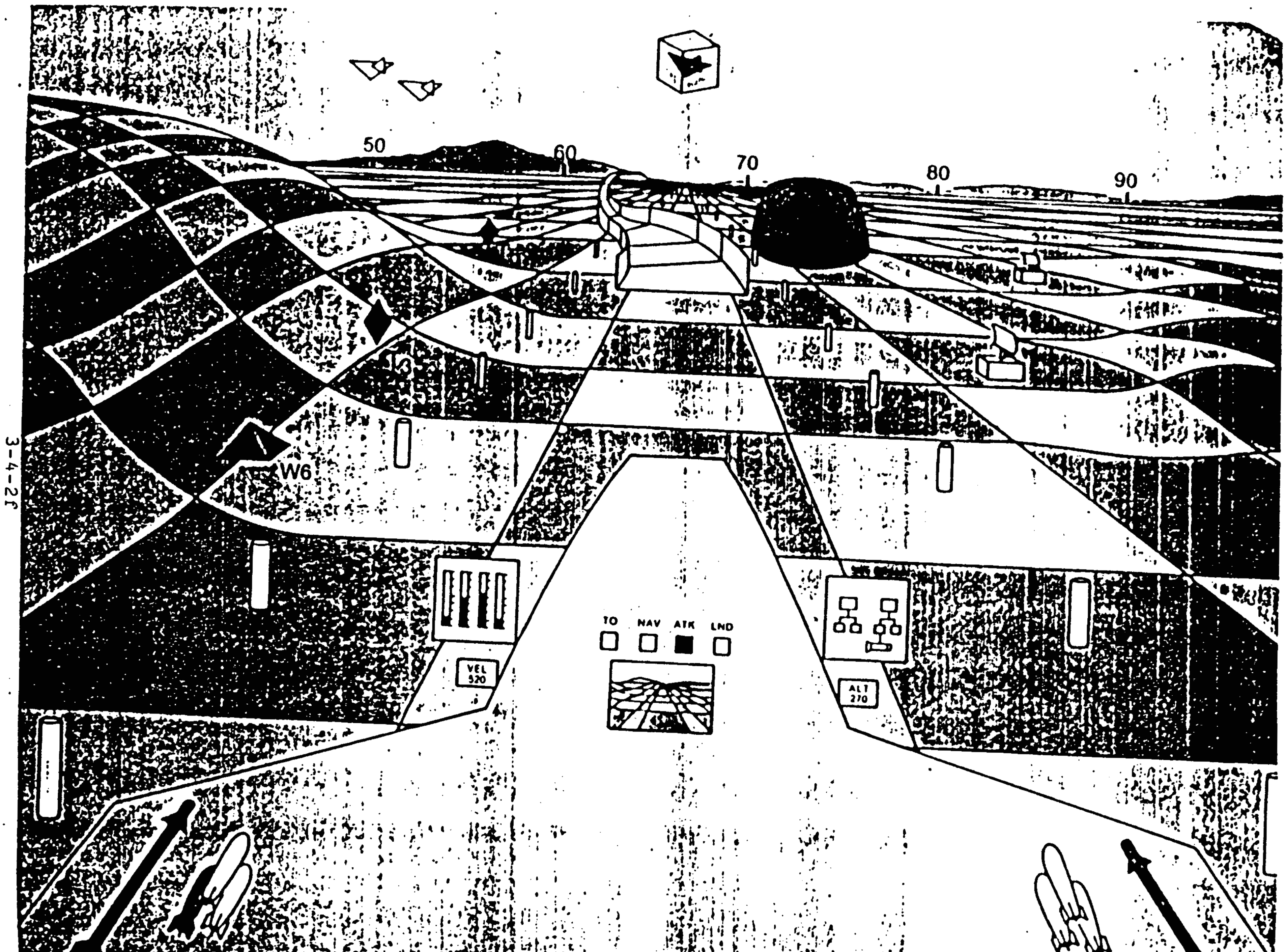
CONTROL PATH
HEAD/EYE SENSING
VOICE ACTIVATION
VIRTUAL HAND CONTROL

OPERATOR

WEAPON
SYSTEM

DISPLAY PATH
HEMISPHERICAL VIRTUAL DISPLAY
BINAURAL DISPLAY
TACTILE DISPLAY

HE 83 9 68



50
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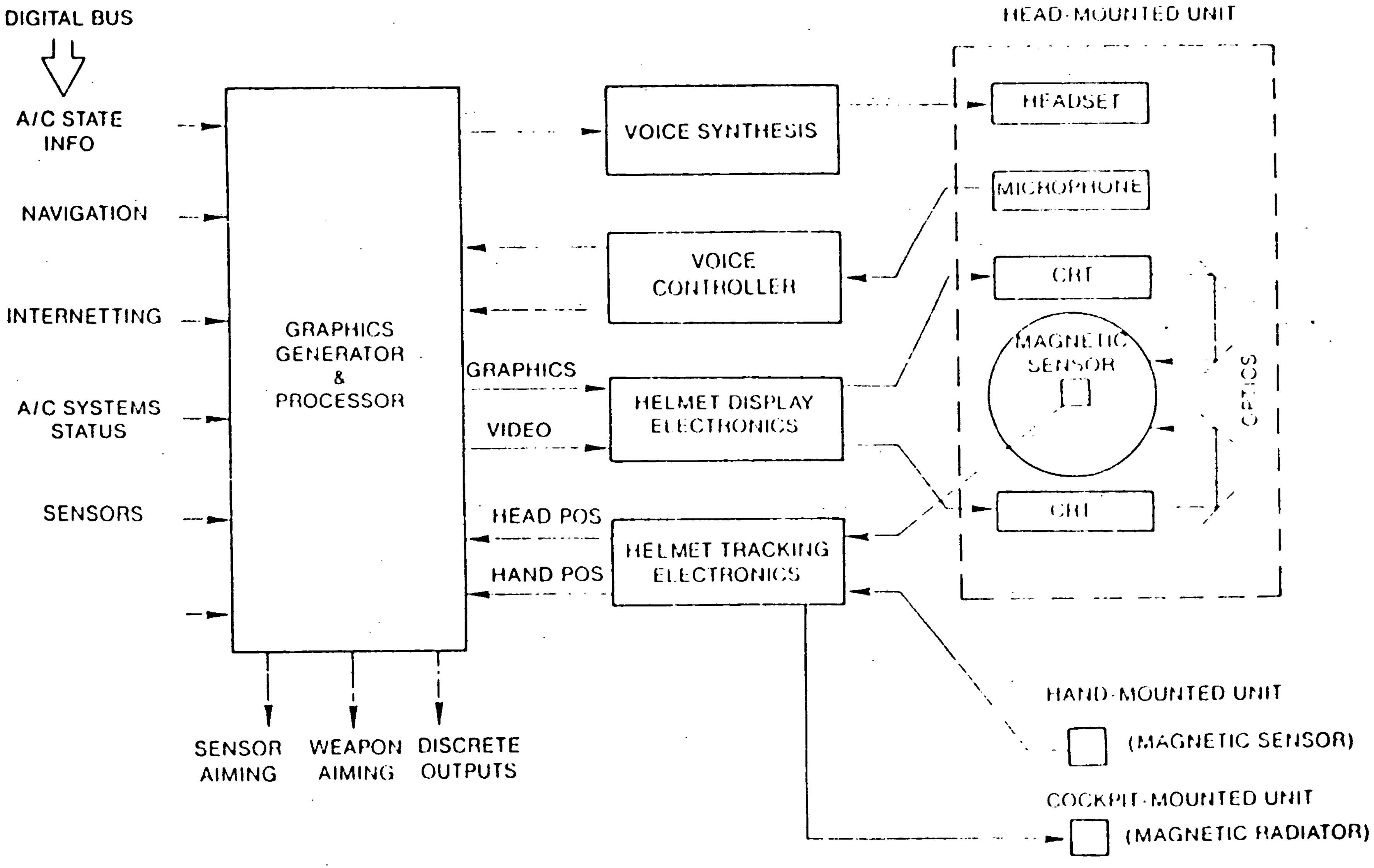
VIRTUAL COCKPIT



DIGITAL BUS

A/C STATE INFO

NAVIGATION

INTERNETTING

A/C SYSTEMS STATUS

SENSORS

GRAPHICS GENERATOR & PROCESSOR

SENSOR AIMING

WEAPON AIMING

DISCRETE OUTPUTS

VOICE SYNTHESIS

VOICE CONTROLLER

GRAPHICS

VIDEO

HELMET DISPLAY ELECTRONICS

HEAD POS

HAND POS

HELMET TRACKING ELECTRONICS

HEAD-MOUNTED UNIT

HEADSET

MICROPHONE

CRT

MAGNETIC SENSOR

OPTICS

CRT

HAND-MOUNTED UNIT

(MAGNETIC SENSOR)

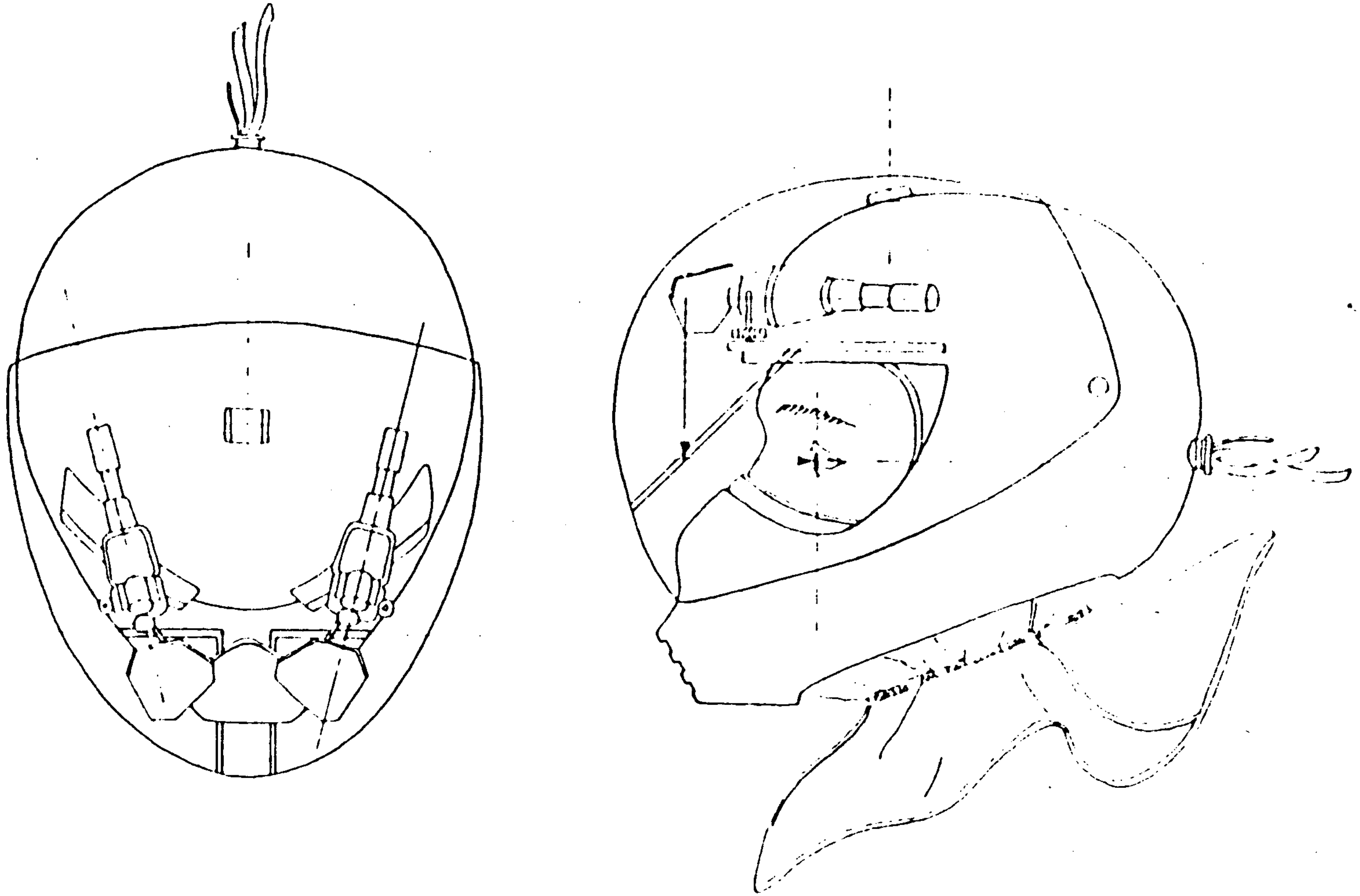
COCKPIT-MOUNTED UNIT

(MAGNETIC RADIATOR)

3-4-28

HE 8428

CONCEPTUAL REPRESENTATION OF A MEDIUM FIELD OF VIEW HELMET MOUNTED DISPLAY



HE 84 4 152

ADVANTAGES OF VIRTUAL COCKPIT

- BEST PILOT INTERFACE
  - — MATCHES NATURAL ABILITIES
  - — PROMOTES SPATIAL AWARENESS/VISUAL COMMUNICATION
  - — TAILORED TO PILOT
- CREW STATION DESIGN FLEXIBILITY
  - — INDEPENDENT OF COCKPIT SPACE/HARDWARE
- DRAMATIC COST REDUCTION
  - — **VERY LITTLE** HARDWARE NEEDED
- EMBEDDED TRAINING
- OTHER
  - — CAN BE **RETROFITTED!**
  - — CAN BE **REMOTED!**

HE 83 969

KEY TECHNOLOGIES UNDER DEVELOPMENT

- MINIATURE CRT IMAGE SOURCES
- WIDE FIELD-OF-VIEW/BINOCULAR OPTICS
- 3D AUDITORY DISPLAY
- PRECISION MAGNETIC HEAD/HAND TRACKER
- HELMET-MOUNTED EYE TRACKER
- SPEECH CONTROL/SYNTHESIS
- MINDWARE

THE VIRTUAL UMBRELLA ATTITUDE INDICATOR

Emily Howard
Department of Psychology, UCLA

BIOGRAPHY

Emily Howard was born in Tallahassee, Florida in 1959. She obtained her B.A. degree cum laude in psychology from Franklin & Marshall College in 1981. Ms. Howard attends the University of California, Los Angeles where she completed her Master's degree in psychology in 1983 and is currently completing her dissertation on the subject of human visual perception. In 1985, Ms. Howard accepted an internship to conduct research on the design of visual displays in the Air Force Aerospace Medical Research Laboratories. She is a member of several scholarly and professional societies, including Phi Beta Kappa and the Association for Research in Vision and Ophthalmology.

The previous speaker, Tom Furness, has shown you something of what the cockpit of the future will look like. It will be my job to show you what the attitude indicator of the future will look like. This presentation comes out of a project that Tom and I started early in the summer of 1985. Tom approached me initially with the idea of designing an attitude indicator for the VCASS which directly addressed the problem of pilots' spatial disorientation. He proposed that we design an indicator which would stimulate peripheral vision, particularly to take advantage of the wide field of view in the helmet-mounted display. Now, from what we've heard from earlier talks, this would seem like a very plausible idea, based on the evidence presented by Dr. Leibowitz on the focal and ambient modes of visual processing and on the success of Dr. Malcolm's Horizon indicator. But from my background in visual science, this seemed like a rather curious idea. From what I knew of the research comparing foveal sensitivity to peripheral sensitivity, my impression of the peripheral retina was that it was basically "big and stupid," when you compare it with the remarkable capabilities of the fovea. Virtually every set of results you encounter in visual sensitivity research finds the fovea superior to the periphery across a broad range of measures. These measures include acuity, contrast sensitivity, temporal frequency sensitivity, color perception, and even movement thresholds. There seems to be this myth that peripheral vision is somehow specialized for motion perception, but in truth the fovea has proven to be more sensitive when tested at what might be considered the extreme limits of movement perception.

So when Tom suggested this approach, I needed to be convinced that in fact the periphery was a good place to put any information, let alone such vital information as aircraft attitude, given that the fovea is indeed so much better in nearly every way. Thus, I went back to the literature and uncovered, to my knowledge, the only paradigm where the periphery actually beats the fovea in a laboratory comparison. Not surprisingly, this paradigm examines the phenomenon of vection, that is, the illusion of self-motion.

In a study by Held, Dichgans, and Bauer, 1975, subjects were tested for roll vection, i.e., the sensation of one's body apparently "rolling" head over shoulders either to the left or right. Roll vection was induced in this study by having subjects view a large patterned disk (subtending 130 degrees) rotating clockwise for several minutes. Afterwards, subjects would typically report the illusion of perceiving their bodies rotating counterclockwise, head over shoulders. Held et al. compared the magnitude of this illusion at several retinal eccentricities. With the patterned disk covered by a mask so that only the central 18° of the disk was visible, subjects experienced a moderate and unambiguous sensation of roll. When the disk was remasked to expose only an outer annular segment (<u>narrower</u> than the radius of the foveal disk) located at 43° eccentricity, the magnitude of the vection illusion nearly doubled! On the bases on these results, I felt convinced. The visual dominance over vestibular cues demonstrated by the periphery in this study argued a strong case for using peripheral vision to display attitude information.

The result, then, of my collaboration with Tom and other members of the VCASS project produced what we call the Virtual Umbrella attitude indicator. As I describe this display, I should also caution you about this presentation. First, the display is still under development and undergoing many modifications. Hence, this presentation can only give a rough impression of what the completed display will look like. Some of the features have already changed even since these viewgraphs were made. In addition, the viewgraphs, and even the videotape I will show you later, do not provide a complete sensation of what the pilot experiences while wearing the helmet display. What you will see in this presentation is the monocular version of the display. Bear in mind that in the helmet, whatever is presented to one eye is also reproduced in the other eye with appropriate offset, to provide a compelling, panoramic, stereo image to the wearer.

Turning now to the presentation, Figure 1 depicts some of the salient features of the Virtual Umbrella attitude display. These include a simulated terrain with horizon to provide a global indicator of attitude, as well as the cues for negative pitch. In the center of the figure is the aircraft boresight, represented as a circle with dashed lines extending on either side of it. This serves as a more explicit cue to the aircraft's attitude relative to the virtual world. Heading makers are displayed in the sky portion of the display in 60° increments as another cue to aircraft position. Also, along the sky "spokes," the vertical lines in the figure, are markers indicating degree of positive pitch. The base of every spoke corresponds to 0° pitch; the next marker above equals 30° pitch. Thus, in this viewgraph, we see from the position of the aircraft reticle that the display is currently depicting straight and level flight, that is 0° pitch and 0° roll, with a heading of

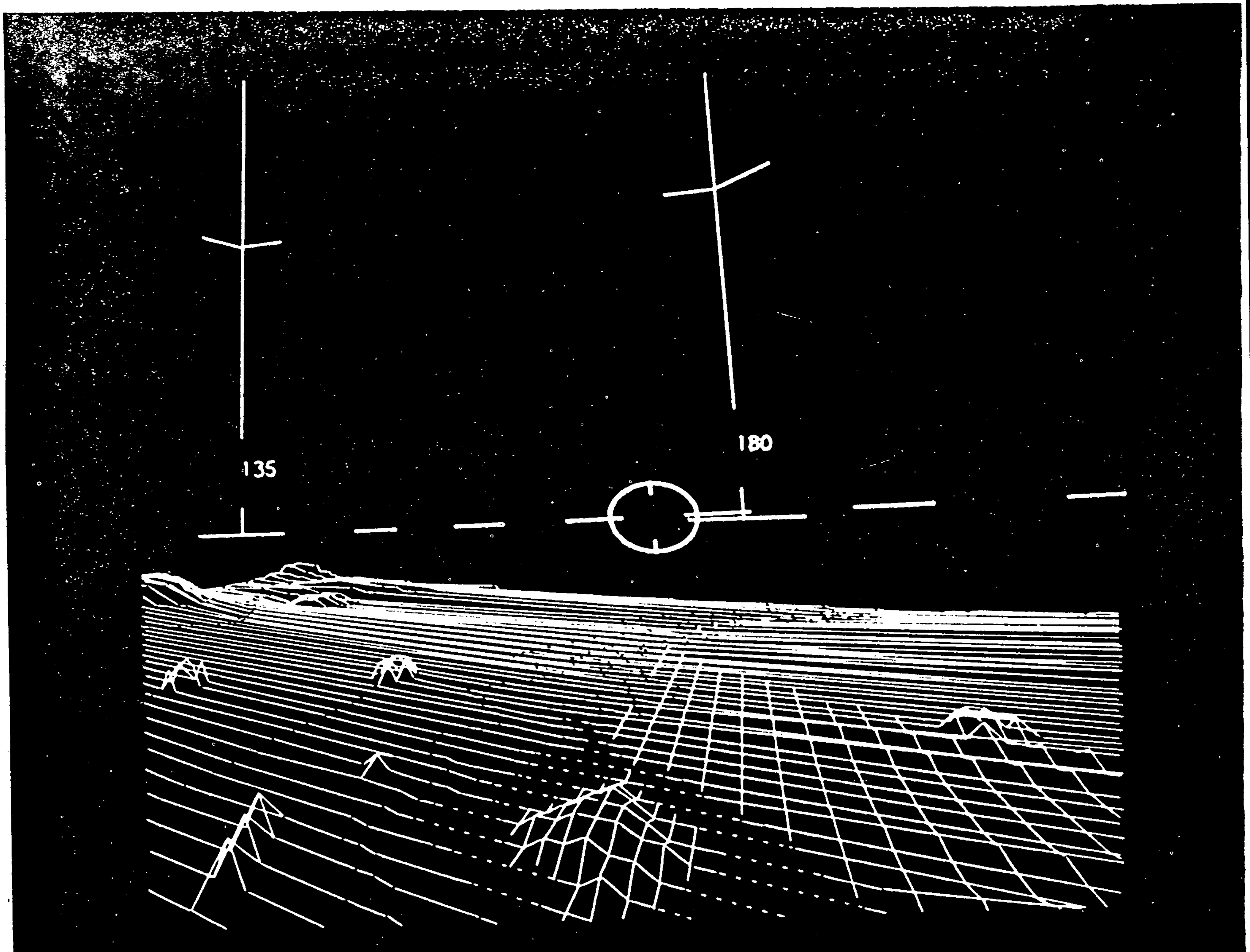


Figure 1

approximately 180°.

These spokes I have mentioned are the pilot's cues to positive pitch attitudes. Figure 2 gives a better view of how these spokes are incorporated within the virtual world symbology. This figure depicts what we term the "God's Eye view" of the VCASS, a sort of outside-in presentation of the virtual world. To create an image for the helmet-mounted display, the computer-generated imagery (CGI) software computes where the aircraft is within this virtual world (outside-in) and projects this information to the helmet display as it would appear to the pilot within the aircraft (inside-out). The small box at the center of this figure is the aircraft, below it is the terrain, and here we see why the name "virtual umbrella" was chosen for our display. These positive pitch spokes surrounding the aircraft are designed to float "apparently" above the aircraft at all times with in this virtual world and indicate flight at positive pitch regardless of heading. This virtual umbrella frame thus becomes a part of the pilot's virtual world, providing a stable and familiar cue to attitude in the same way that a horizon would, but for a fuller range of attitudes than can be conveyed by the horizon (for example, during a vertical climb).

The way that the umbrella depicts attitude is that for any translation of the aircraft on any axis, changes in altitude, forward motion, etc., the umbrella spokes remain aircraft-referenced. They translate, changing altitudes and location above the terrain surface, just as the aircraft does; thus, they have no net motion in the pilot's field of view from within the aircraft. However, with any rotation around any of the principal axes, as in pitch, roll, or yaw, then the upper frame becomes earth-references, so that now there is net motion (along with the terrain) in the pilot's field of view. In summary then, while the spatial location of the virtual spokes changes with the aircraft, their spatial orientation relative to the earth's surface remains fixed. Any net motion of the umbrella frame within the pilot's view of the virtual world thus provides direct correspondence to changes in aircraft attitude (pitch, roll, and yaw).

Although the virtual umbrella is primarily an attitude indicator, we find that a general indicator of altitude is given as well in certain circumstances. In Figure 1, I should point out that the base of the umbrella frame is always fixed in the altitude plane of the aircraft, so that the distance separating the base of the frame and the horizon gives at least an approximate measure of the aircraft's altitude. Next, I would like to show you some different attitudes to demonstrate how the display operates. Figure 3 depicts the aircraft at 0° pitch, now in a left roll of approximately 60°. Figure 4 shows the aircraft back at wings level, now beginning a climb to 30° pitch. Increasing the angle of the climb, Figure 5 shows the aircraft has now achieved a pitch of 60°. At this angle, the horizon is no longer visible, and the apex of the umbrella frame, indicating 90°, comes into view. Despite the lack of horizon, the pilot's perceptions of pitch and roll are unambiguous.

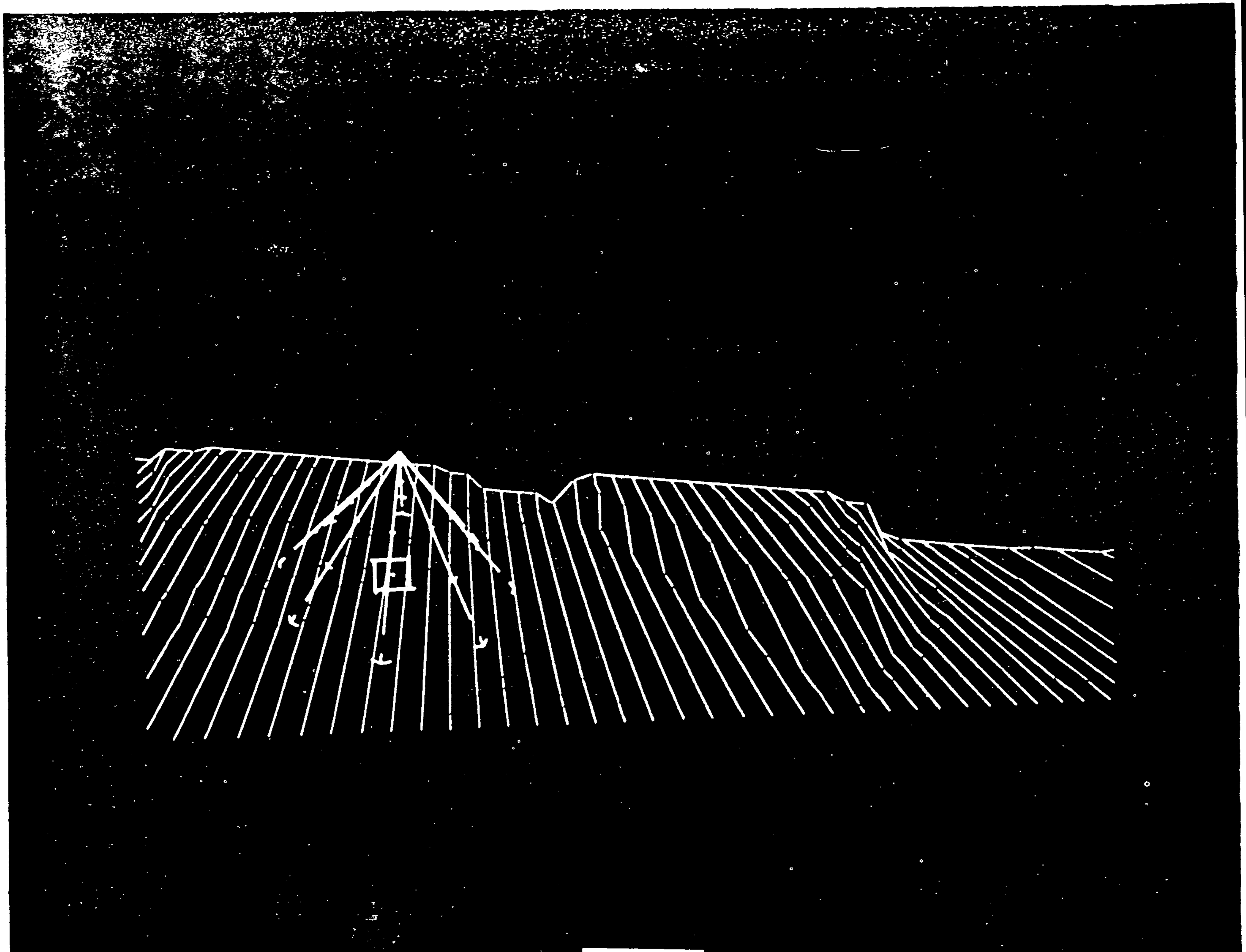


Figure 2

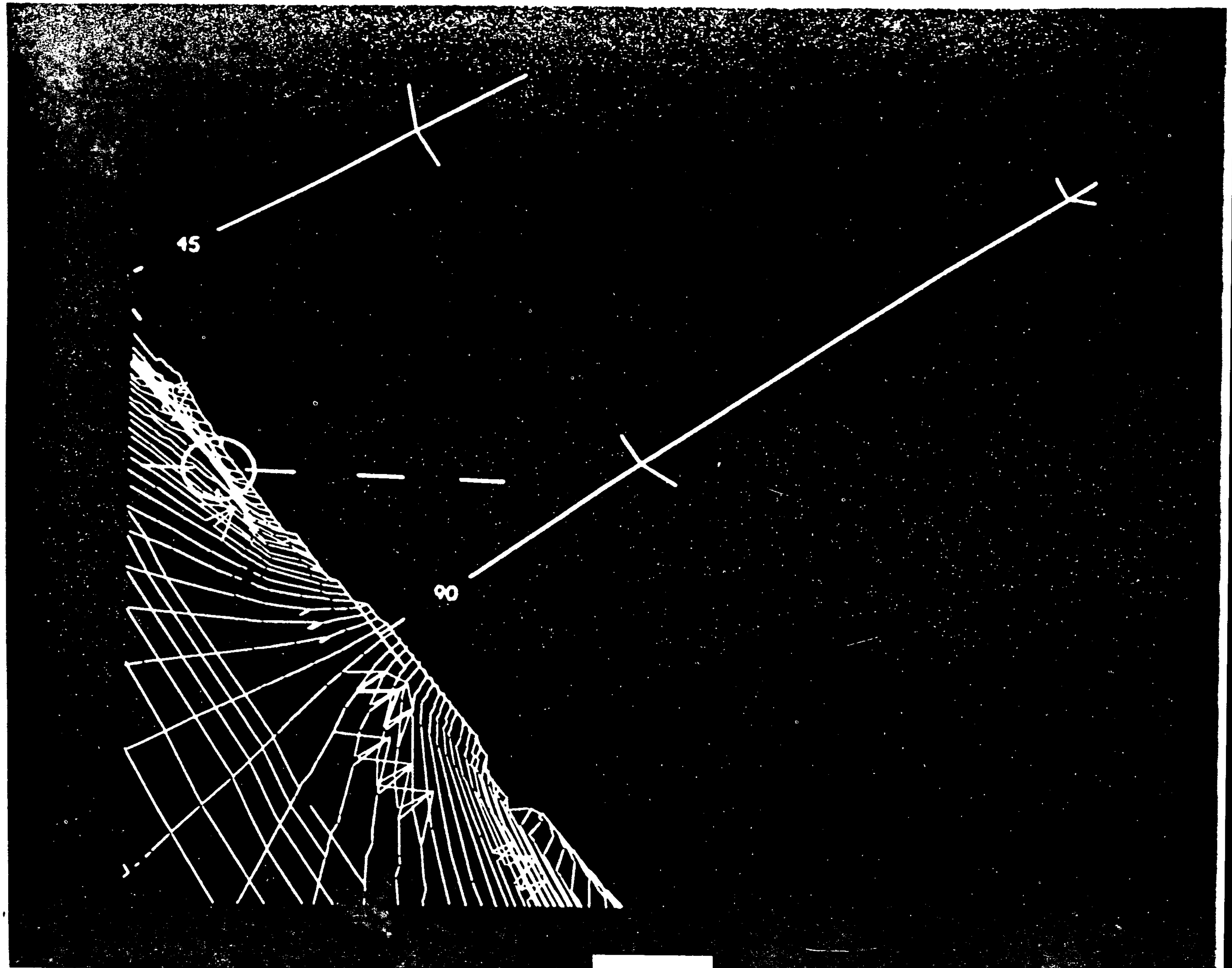


Figure 3

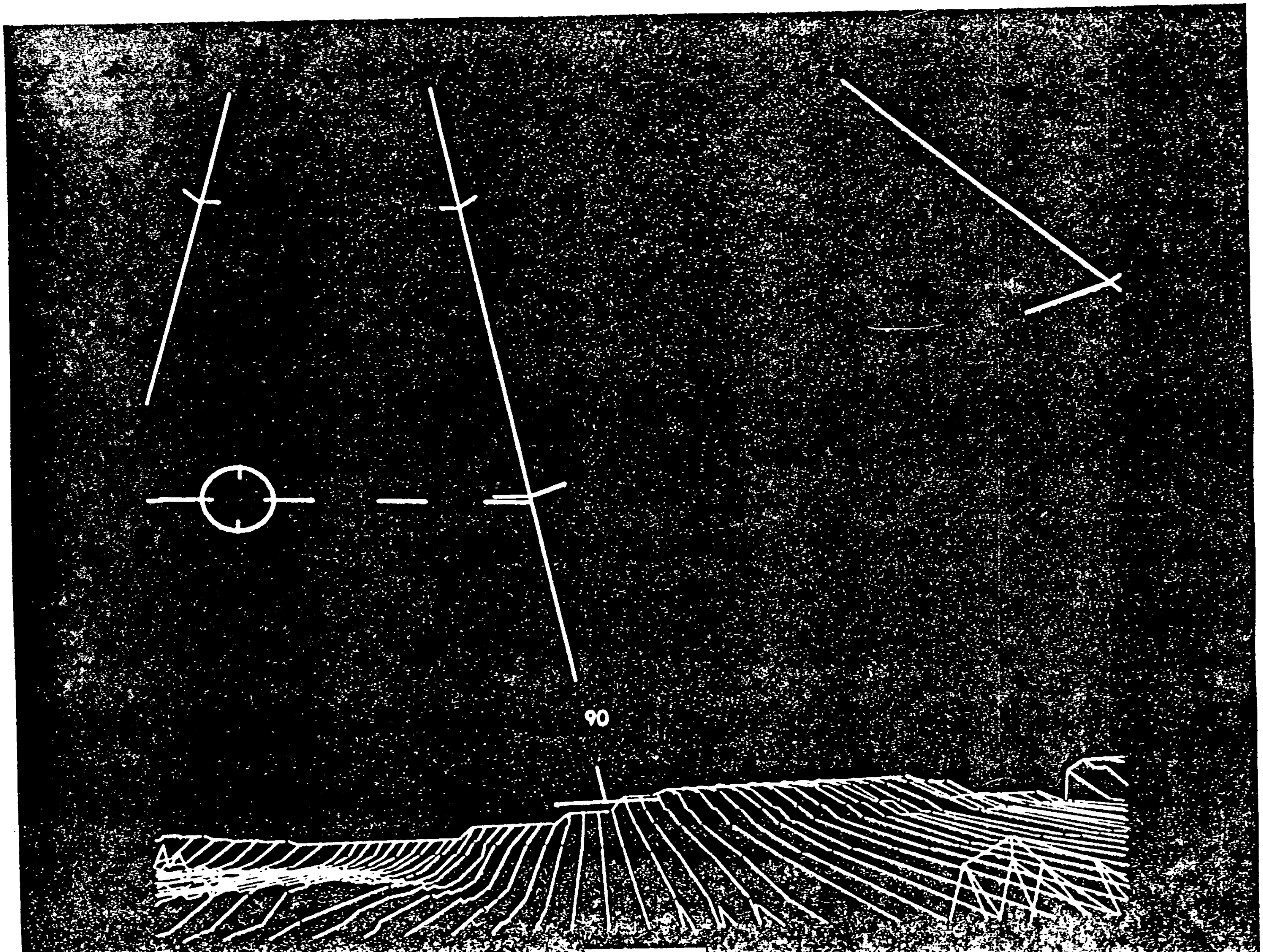


Figure 4

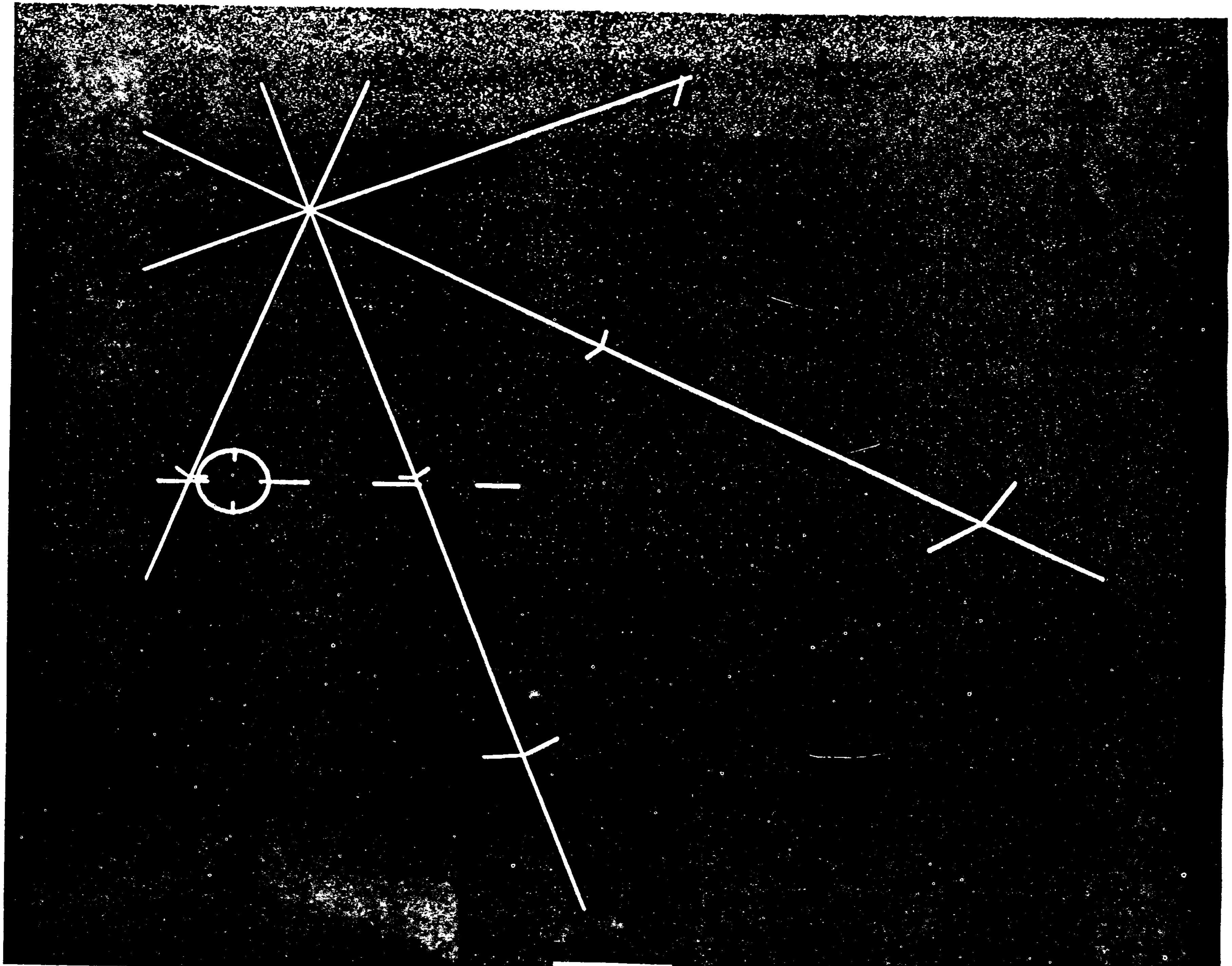


Figure 5

In Figure 6, the aircraft has continued increasing the pitch angle through vertical and into an inverted dive. The pilot has returned again to level flight though now inverted. In this inverted attitude, of course, the terrain and horizon appear at the top of the display and the spokes of the frame radiate upward. Finally, to demonstrate what negative pitch looks like to the pilot, in Figure 7 we see the aircraft more or less in a straight dive (and also at a very low altitude. I think, in face, that this simulator crashed in the course of taking these photos). You can see that linear perspective and motion parallax become the important attitude cues when the aircraft is in a nose low attitude below a visible horizon.

I would like to wrap up this presentation by discussing some of the limitations that we see still exist with the Virtual Umbrella display. As I mentioned previously, this display is still under development, and there remain several features which need to be incorporated to complete the task of providing good attitude awareness to the pilot. Many of these comments, by the way, were brought to our attention by a group of pilots who participated in a preliminary study comparing the Virtual Umbrella display with the HUD and the traditional ADI.

First, there is no precise indication of air speed, though for the most attitudes there are some motion cues available in the rate of change in the terrain. However, when the terrain goes out of view entirely, as in a steep climb, there is no visible perception of motion at all. Also, precise altitude information is lacking. Although a gross indicator may be found between the base of the frame and the horizon, particularly in dives where altitude information is crucial, there do not seem to be enough cues in the changing size of the terrain features to provide precise altitude control. Finally, a type of indicator such as a horizontal situation display, conveying spatial location with respect to the earth, is not yet available and needs to be incorporated within the display in some manner.

In conclusion, though there are still improvements yet to be made to the Virtual Umbrella display, many advantages can nevertheless be seen in its unique design. First, the display offers a wide field of view, permitting naturalistic depiction of attitude cues in addition to stimulating peripheral vision. Both of these features make the display more likely to tap into sub-attentive processing of aircraft attitude, requiring less focal attention to the task, and thereby reducing pilot workload. A second advantage is that a helmet-mounted display remains in view at all times, regardless of head position. Consequently, the pilot should find it difficult, if not impossible to ignore attitude checks. Thus, this tendency "to forget to fly the plane" while caught up in the demands of the mission, often cited as a major source of spatial disorientation, can be completely eliminated. Further, not only does the helmet-mounted display remain in view at all times, but it also maintains <u>complete control</u> over the pilot visual field. Consequently, there should be no opportunity for spatial disorientation resulting from reflections, glare, unusual clouds, or other common visual illusions.

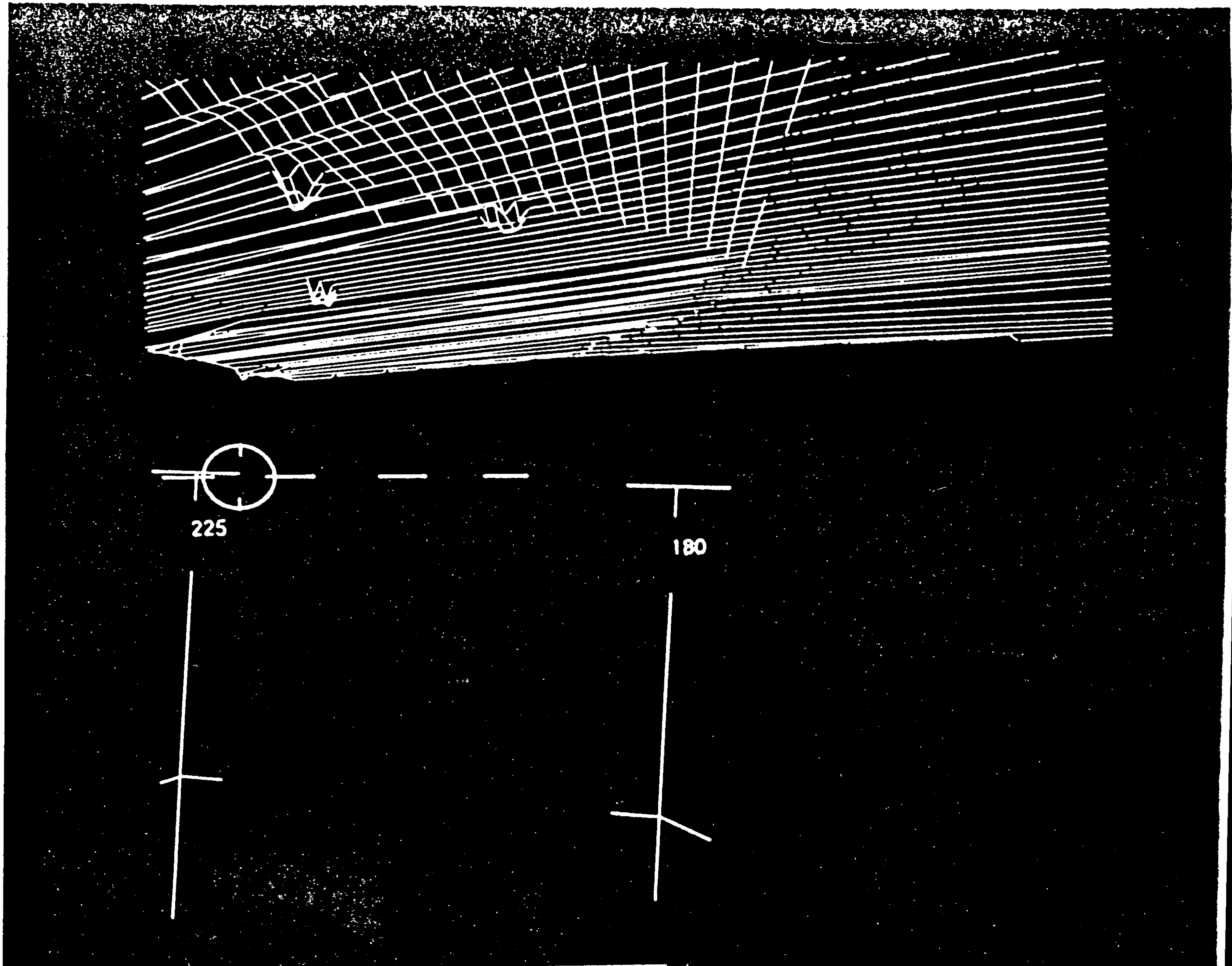


Figure 6

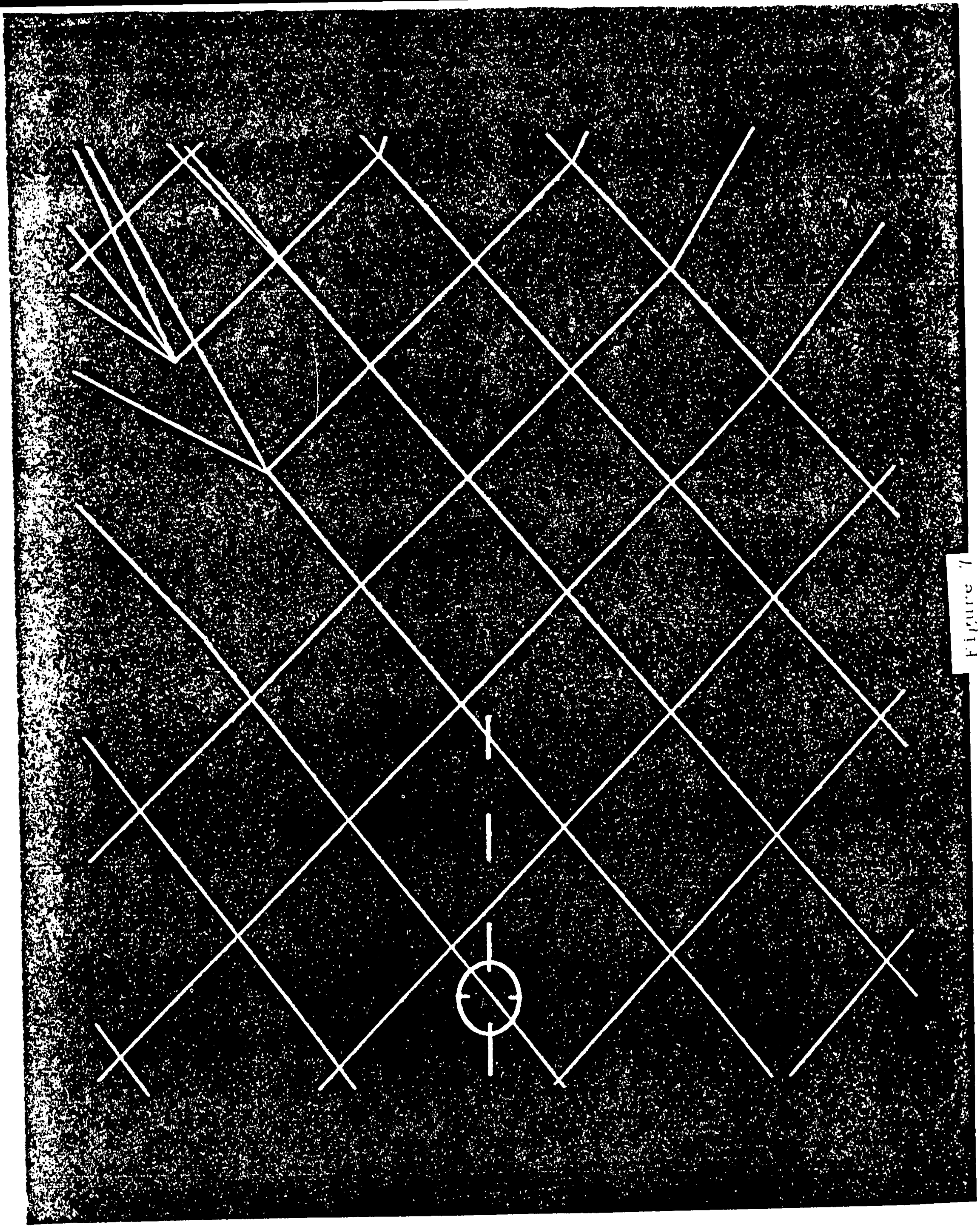


Figure 7

Finally, the concept of visual dominance, the salience of a visual cue for describing the sense of where the body is in space, can be considered as a third advantage to the display. Not only can the display be used to override any conflicting vestibular illusions pertaining to attitude, but with the helmet, the pilot may be located in any part of the aircraft and in any position, reducing the impact of vestibular and other physiological side effects to a minimum. By commanding the pilot's vestibular sensations of attitude accurately and at all times, we may ultimately eliminate spatial disorientation entirely.

QUESTIONS AND ANSWERS

Richard Haines: Emily, could you share with us some of the flight performance techniques you're going to use to evaluate the display?

EH: As a matter of fact, we just completed a study comparing the traditional ADI and a HUD with the Virtual Umbrella. We used two measures, one being response time necessary to recover from an unusual attitude. The display would be dark and the pilot would be warned that an unknown attitude was about to be depicted, the display would come up, and we would simply measure the time it took for them to recover from that attitude to straight and level flight. The second measure was an estimation of control reversal, the number of times that the pilot reversed the direction of the stick in order to regain straight and level flight, as an indication of how naturalistic this display was or how simple it was to encode the correct attitude from the display. Although the data also have not been fully analyzed yet, there emerged several artifacts in the study which unfortunately confound many of the comparisons on the flight performance measures. However, we did find some interesting results from a questionnaire that we administered to our pilots.

In comparing previous experience with displays among our subjects, many had never seen anything but an ADI, or 99% of their experience had been with an ADI, but in asking pilots to state their preference, ranking the displays in order 1, 2, and 3 where 1 = most preferred, 3 = least preferred, across the six pilots the ADI had an average rating of 1.4, the Virtual Umbrella had an average rating of 1.6, and the HUD had an average rating of 2.5. So at least in the questionnaire, we found results more akin to what we were hoping to find, that the Virtual Umbrella has many features which are desirable and preferred by pilots, we just haven't yet created the appropriate test conditions to observe these in pilots' performance.

Unidentified: Just looking at the display from your slides, its very powerful to me in the "up" mode, but not so powerful in the "down" mode. I would suspect that (pilots) would do better recoveries from a nose high than they would from a nose low. Have you had any results to that effect?

EH: Your observation also reflects one of the primary comments that we received from the questionnaires, and although we haven't looked at that yet in our performance measures, it's one of the questions we want to ask. In our first analyses we simply summed across all the attitudes that we depicted. But we did sample from the full spectrum of attitudes and we now have the opportunity to go back and recategorize the data and do that.

Unidentified: I have an adjunct to that question, and I'm sure that on the tape it will be more obvious, but its not obvious to me how you determine from your dive picture what to do. I'm sure there would be some sort of perspective view, but I don't get a feeling of how you would know to roll to the nearest horizon and pull, because I'm not sure it tells you which way to roll.

EH: One of the things that is missing from this display is motion parallax, which is a strong cue added to linear perspective as to what would be the appropriate recovery.

Tom Furness: I can comment on that also. The display you see in the viewgraphs is not what we are portraying for the LHX. In fact, this is an older generation display. The grid lines that were portrayed for the terrain in the LHX studies gave the crew member, depending on the projection of the lines, the vanishing point of where the horizon was. And the only time there was any ambiguity was when you were going straight down, because you would see the grid work as being square. But if you were in any other attitude, you would know by a projection of the vanishing point, where the nearest turn was to get to the horizon. And so that's the way it was conveyed. the crew members, however, felt that there needed to be a more rich or robust method for portraying (the terrain) than what we had. But there was a way that was sort of intuitive when you saw the display, sort of like looking at a checkerboard and orienting it in different directions. You could tell by its orientation what your attitude reference was to the horizon.

Unidentified: What happens to these helmets when they get scratched or wet? How much care do they need to have to keep them working? Are these very susceptible to scratches?

Tom Furness: If we can solve the problem for the Army, we can solve it for the Air Force. You thing that you have problems?!

Unidentified: You don't feel that this display would be a problem obstructing natural features (while in the transparent mode), creating additional clutter and blocking out targets, do you?

EH: The question of clutter is one that we're still considering--the idea that this display is designed for peripheral vision seems to question why should we have anything in the immediate foveal vision. One thing we'd like to try is eliminating the umbrella spokes themselves from foveal vision. We weren't able to achieve this in the initial execution, but it's one possibility.

Richard Malcolm: I may have a strategy that will help you. If you're going to pick up where the eyeball is looking, you may want to take the central two degrees of the field of view and dim down the brightness of the computer-generated imagery. Not so that it vanishes, but so that it actually goes down in intensity, and so that it doesn't mask what's out there where your attention is, but is dies still provide a small amount of calibration. In other words, it will still complete the picture. You don't want to drop things out of the picture, but at the same time its not interfering with where you should be attending on the outside.

Unidentified: Have you flown in an airplane or in a flight simulator equipped with a visual display system (simulated real world background) yet?

Tom Furness: I can comment on that. Remember that the original impetus for this work was to provide a completely IFR presentation. We're making the assumption that you're flying at night and can't see anything. And everything to allow you to recover from an unusual attitude would be presented to you in this instantaneous display. And therefore, at least at this juncture, we wanted to look at how well we could do that compared to the conventional methods. The follow on work we intend to do is now how do you impress this image on a real world type scene. For example, if there is a real world scene there, there's a chance that you don't even have to worry about doing the terrain part of it. Or you might want to do the terrain part of it as fuction of what the ambient luminance is or the visibility of the ground. So therefore, since this is just an initial stage, we felt that putting it on the terrain would confound our experiment, when in fact we understand that a lot of problems occur in situations where you're in IFR conditions. You're flying in a cloud or at night, an inversion occurs, and recovery under these conditions becomes the issue, so that's why we proposed to do that.

Unidentified: It seems to me that I remember, Tom, that in one study on the use of FLIR imagery, they found it very important to have a one-on-one registration with the real world, so that when the real world becomes visible, there is no perceptual confusion. And I think that's something we must all keep in mind when we do display imagery.

(At the end of the presentation, a videotape was shown depicting the Virtual Umbrella attitude indicator in dynamic operation.)

REFERENCE

Held, R., Dichgans, J., and Bauer, J. (1975) Characteristics of moving visual scenes influencing spatial orientation. *Vision Research*, 15, 357-365.

MODIFICATION POTENTIAL FOR THE HUD CONTROL PANEL

Mr. William Augustine
Air Force Flight Dynamics Laboratory (AFWAL/FIGR)
Wright - Patterson AFB, Ohio 45433

BIOGRAPHY

- Graduated from Rutgers University in electrical engineering 1961
- Commisioned in the Air Force and served at Wright Patterson AFB as a Flight Test Engineer 1961-1964.
- Received a Master of Divinity degree from Central Baptist Seminary 1968.
- Engineer with ASD 1968 to present. Since 1972 worked in Head Up Display development. Managed efforts to provide Head Up Displays for the T-38, C-5 and the CH-3 Mid Air Retrieval System. Presently involved in Head Up Display improvements utilizing holographic and flat panel technologies.

Abstract

In modern single seat fighter aircraft such as the Air Force's A-7, A-10, F-15, F-16 and the Navy's A-7, F-14, and F-18 the Head Up Display whether approved or not is being used by a majority of pilots as the primary flight reference system. The reason is obvious, the HUD instrument references can be seen along with the real world in an integrated and easily interpreted fashion. The HUD however suffers from two problems when used to recover from unusual attitudes: (1) because the HUD view must be transparent it is difficult to present contrast between sky and ground; and (2) because the HUD has limited field of view and the pitch ladder as currently used is one to one with the real world the ten degree graduations move swiftly through the HUD window making interpretation difficult. This briefing discusses a few methods of modifying the HUD control panel to present additional attitude information.

Discussion of Viewgraphs

(Viewgraph One)

Early cockpits with few instruments were designed for VFR flying. Not very good at night or in weather.

(Viewgraph Two)

Later thru the F-4, poor outside visibility and good instruments meant good at night and in weather IFR flying. The ADI along with airspeed, altitude and the HSI were the primary flight reference, "T" cockpit configuration.

(Viewgraph Three)

Although not certified, the HUD in the high visibility cockpit of modern fighters has become the primary flight reference.

(Viewgraph Four)

The symbology on the HUD is inadequate to alert the pilot of inverted flight. The two formats are probably 95% alike. Coupled with body sensor information, which might appear normal, the pilot can very easily become unaware of his true orientation.

(Viewgraph Five)

The ADI two color or black and white ball is easy to interpret. At a glance, the pilot is aware of inverted flight. The two displays are 95% different.

(Viewgraph Six)

Some of the problems associated with AFR flying utilizing the HUD:

a. The HUD as it is today with present symbology, is inadequate to replace the ADI.

b. There is no standardized basic flight training in the use of the HUD. No crosscheck training. The Air Force needs basic HUD training in crosscheck and procedures. The French use HUD equipped trainers. Our T-38 program needs to be updated. AFWAL and IFC are preparing a program to fit two T-38s with HUDs.

c. Continued dependence on the HUD, especially by pilots with limited experience may cause head down instruments to be little used even when they provide better IFR information.

d. A quick look at todays cockpit is enough to see that the ADI has been delegated a less prominent position in the cockpit. A pilot in an emergency situation may be forced to search for his ADI.

(Viewgraph Seven)

AFM 51-37 specifically states that the HUD is not to be used as the primary flight system. Pilots would do well to heed this advice.

(Viewgraph Eight)

Possible Solutions:

Short Term Symbology - AFWAL/FIGR and many other USAF and Navy efforts are directed toward symbology improvements.

(Viewgraph Nine)

Explained in the following viewgraphs.

(Viewgraph Ten)

The Peripheral Vision Horizon Display which is a pitch and roll stabilized horizon line painted across the instrument panel is being flight-tested in an F-16 A/B aircraft at Edwards and Eglin. The purpose of the display is to give the pilot a natural way of observing attitude without taking his attention away from performing his other functions.

It may be possible to project simple ADI information right on the HUD control panel. It also may be possible that when flying at night or in weather, to have a two color raster split at the horizon.

(Viewgraph Eleven/Twelve)

These two viewgraphs of a flat multifunction control panel illustrate how an ADI display might be integrated into the control panel to give an ever present attitude display. An automatically timed ADI program might also be possible on selected MFDs in order to present ADI information at preselected intervals or to refer back to an ADI presentation after intermittant multifunction use.

(Viewgraph Thirteen)

Another possibility might be to use a holographic fold/mirror that reflects green up on the HUD and passes red and maybe full color to a faceplate for an ADI display.

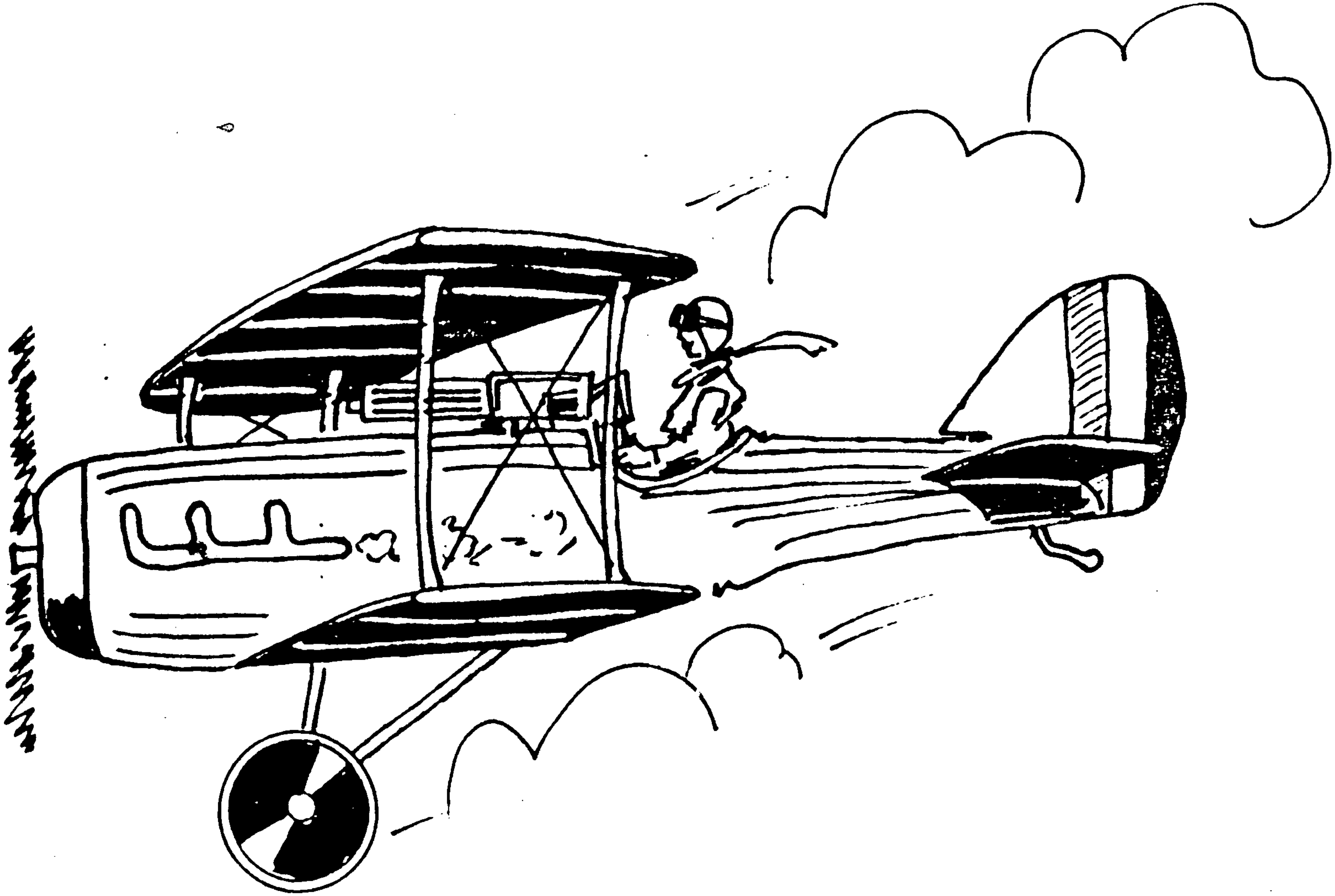
(Viewgraph Fourteen)

The use of back to back fold mirrors would take advantage of the space behind teh HUD foldmirror allowing the HUD control panel to be put further down.

(Viewgraph Fifteen)

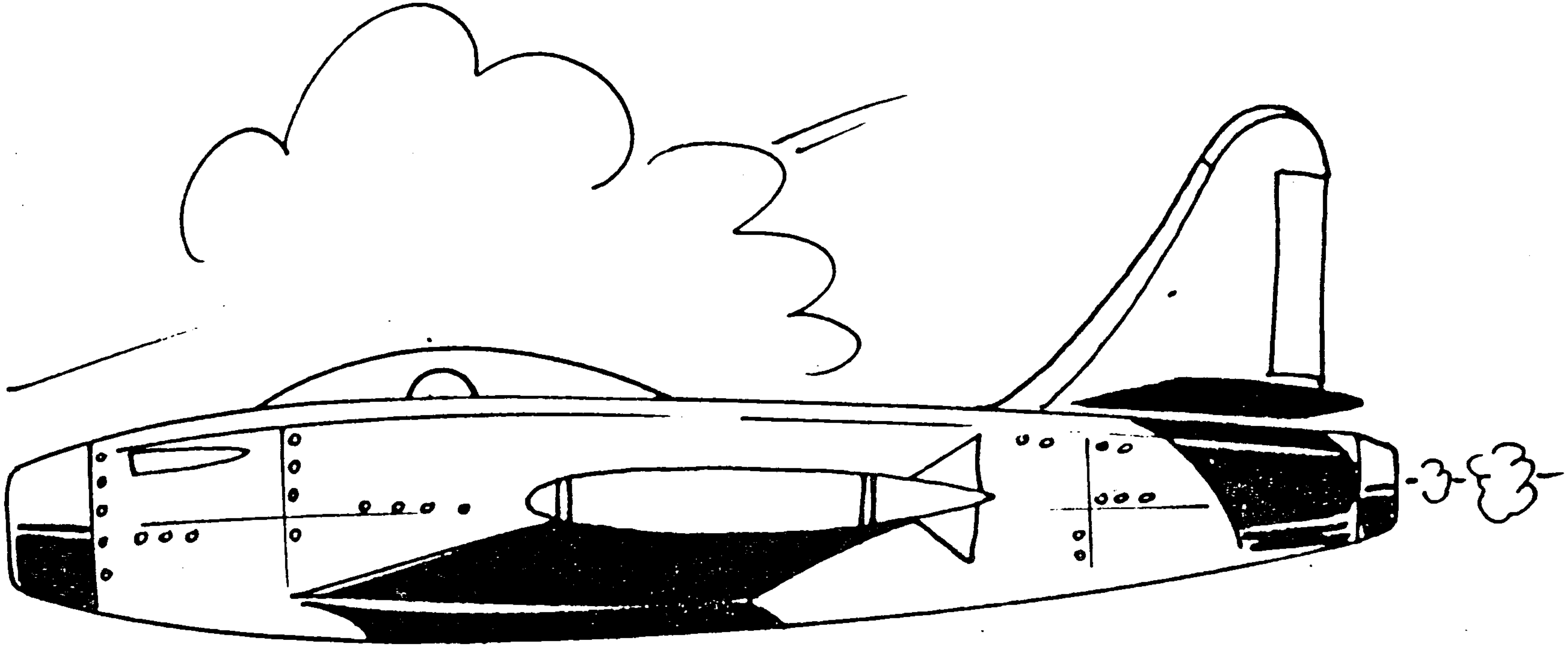
Other ideas - This GEC Avionics idea used a unique combiner to eliminate the fold mirror.

Viewgraph 1



First VFR cockpit - Great·····
except at night in weather

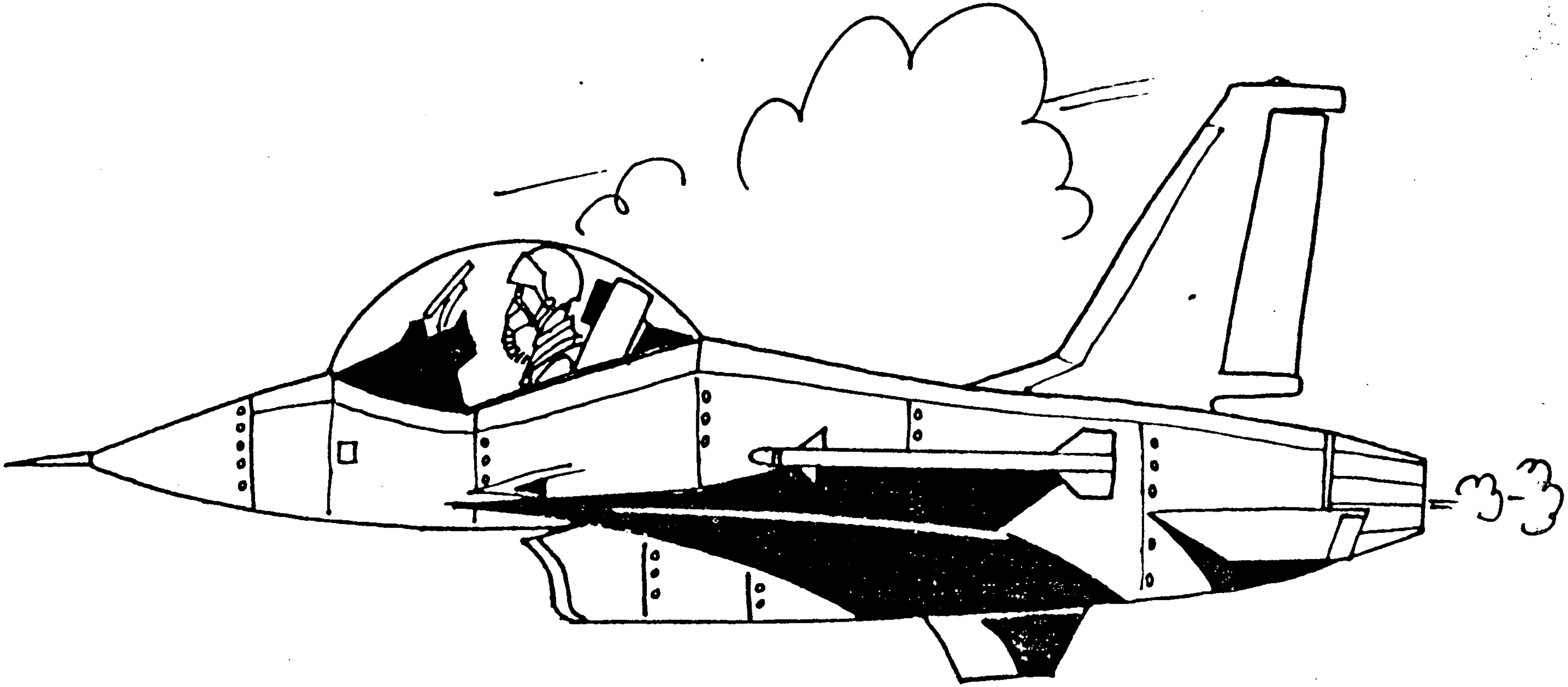
Viewgraph 2



IFR cockpit - Great at night in weather

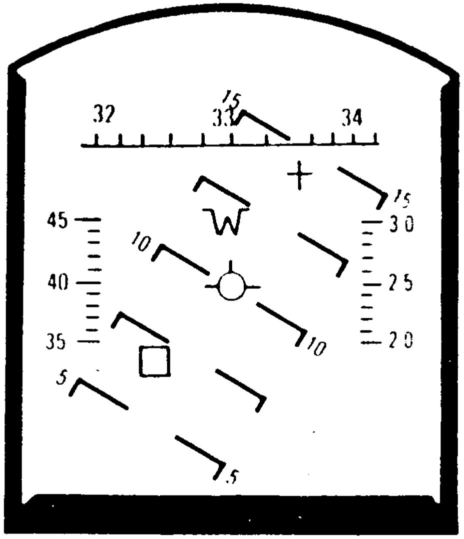
Keep your eyes on the ADI

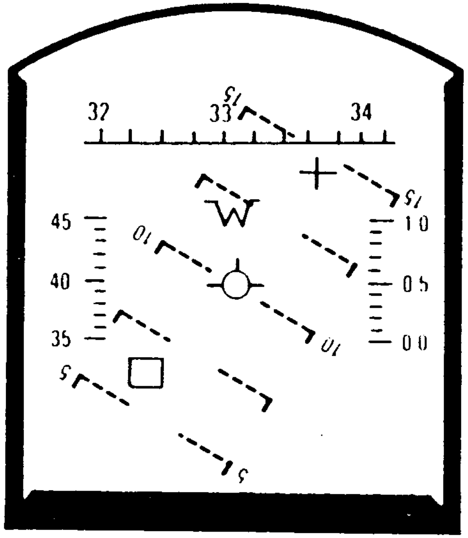
Viewgraph 3
3-6-6

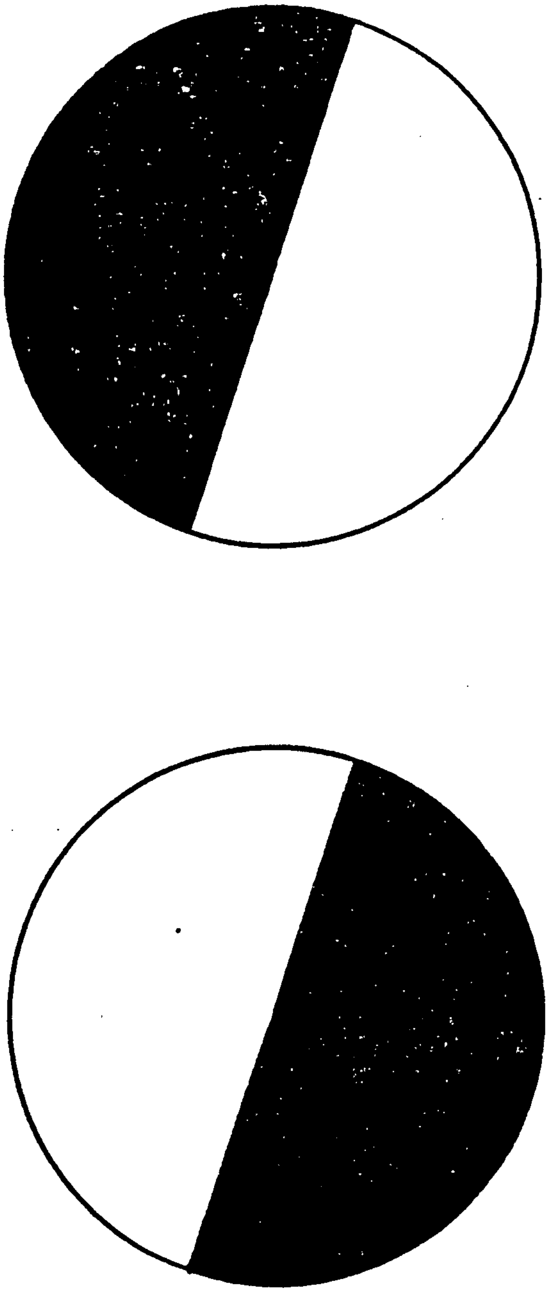


Latest VFR cockpit - Forget the ADI
you have a HUD

IT IS EVEN MORE DIFFICULT WITH CLUTTER







Viewgraph 5

PROBLEMS WITH TODAYS VFR COCKPIT

- HUD (AS IT IS) IS INADEQUATE TO REPLACE ADI
- LACK OF HUD / ADI CROSSCHECK TRAINING
- PILOT LOSES DEPENDENCY ON HEAD DOWN INSTRUMENTS
- ADI DELEGATED TO MINOR POSITION

FACT IS - YOU CANNOT TRUST SENSES / FEELINGS

- YOU MUST TRUST YOUR ADI
- YOU CANNOT TRUST SENSES / FEELINGS
- YOU MUST TRUST YOUR BIBLE

AN ADI IS THE PILOT'S BIBLE

PROBLEM:

- THE HEAD UP DISPLAY IS BEING USED AS THE PRIMARY ATTITUDE REFERENCE

AFM 51-37

1. HUDS DO NOT PRESENTLY HAVE ADEQUATE SYSTEMS TO MONITOR AND ALERT THE PILOT OF ALL SYSTEM FAILURES

2. THERE MAY NOT BE ENOUGH INFORMATION DISPLAYED TO SAFELY FLY IN ALL INSTRUMENT CONDITIONS

POSSIBLE SOLUTIONS

SHORT TERM

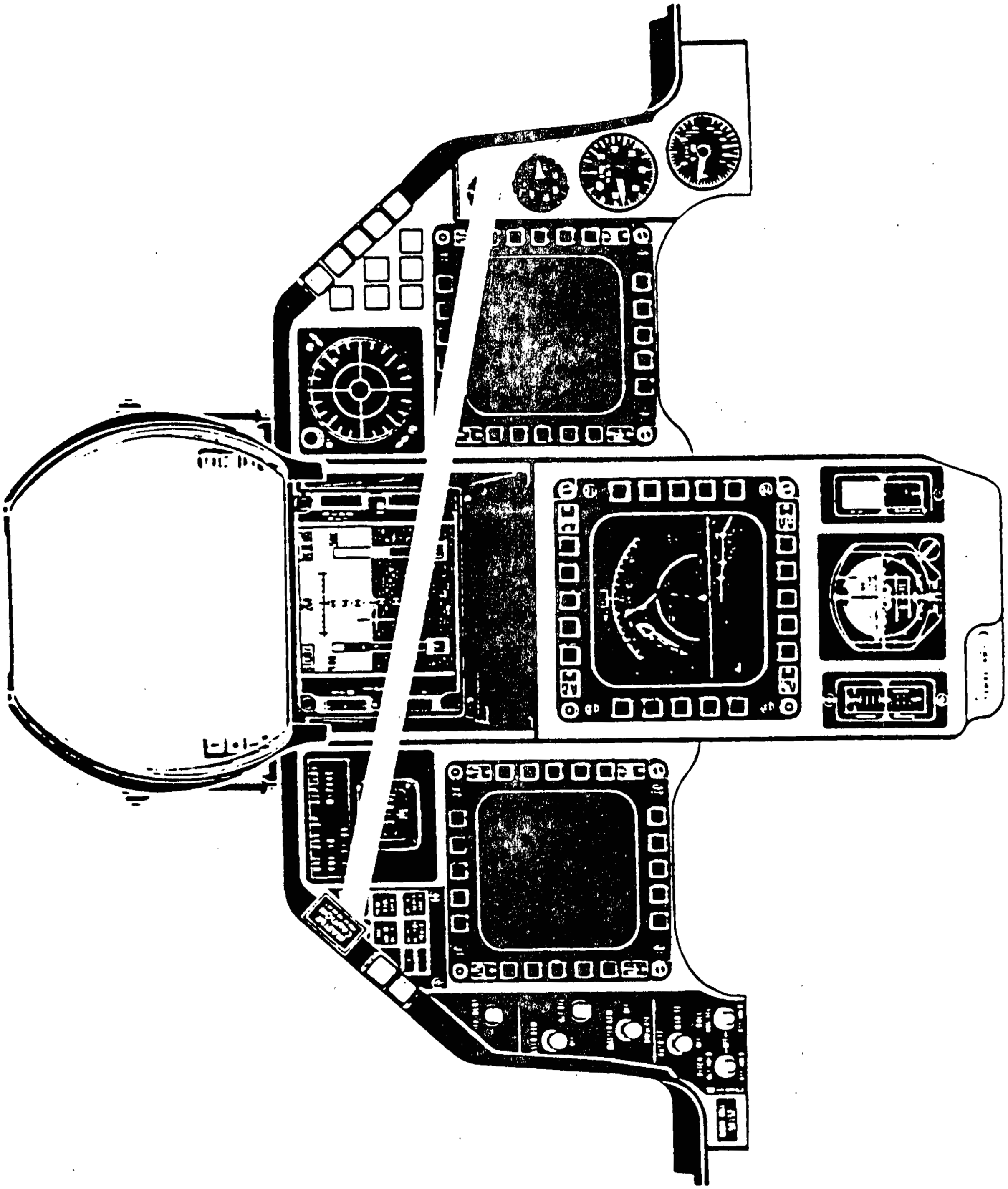
- IMPROVE HUD SYMBOLOGY AND ATTITUDE INFORMATION
- TRAIN PILOTS TO CROSS CHECK MORE
- ADD ADDITIONAL ATTITUDE INFORMATION

LONG TERM

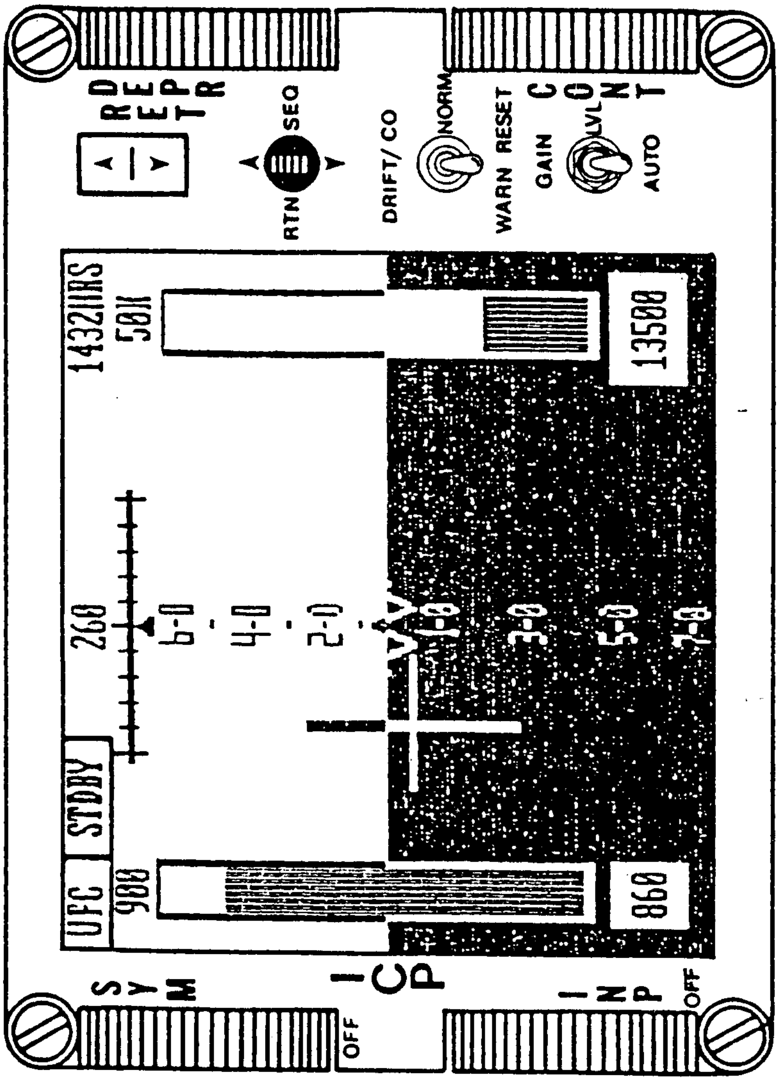
- RE-EMPHASIZE THE ADI IN COCKPIT DESIGN

ADD ADDITIONAL ATTITUDE INFORMATION

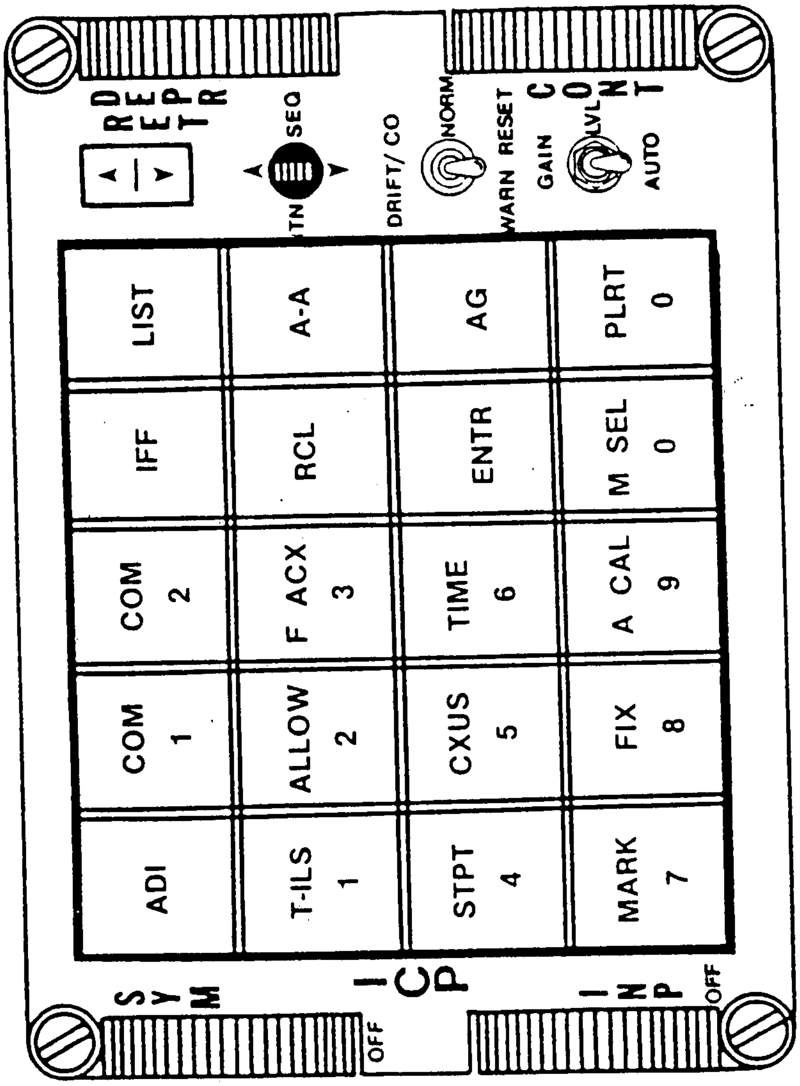
- PVD
- ADI PROJECTIONS
- FLAT PANEL ADIs
- MAKE ADI INFO PRIMARY ON MFDs



Viewgraph 10

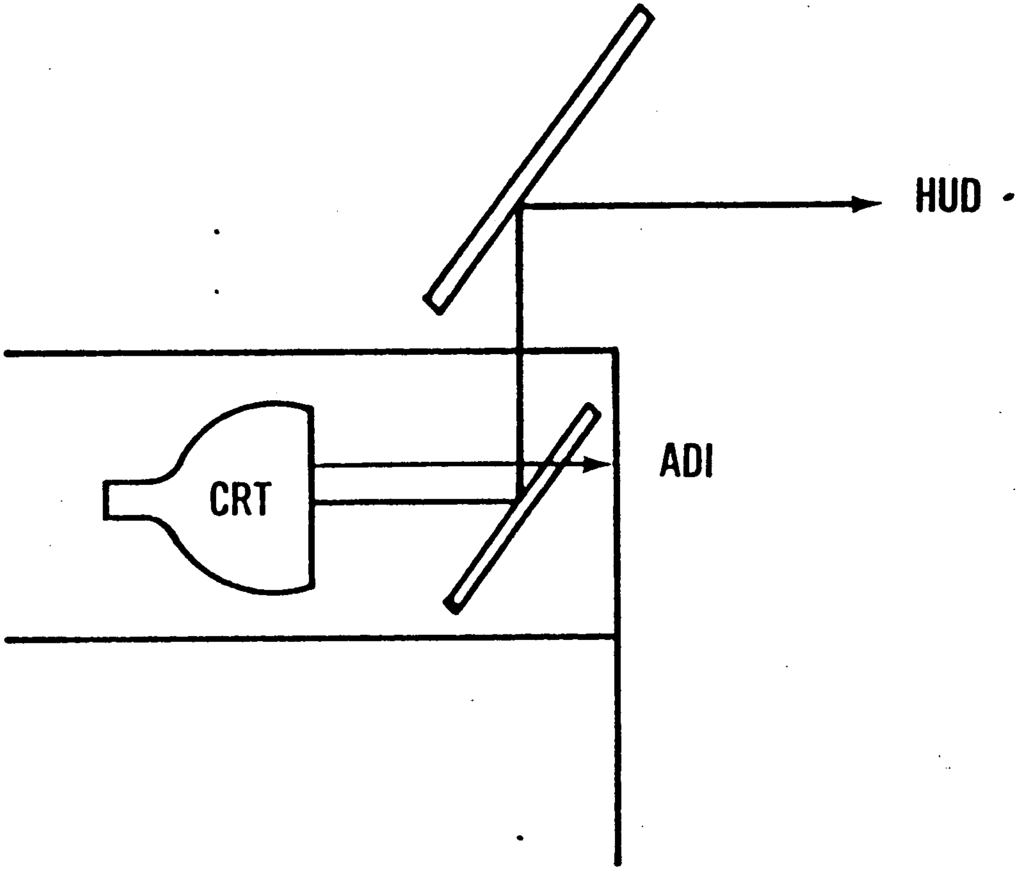


Viewgraph 11



Viewgraph 12

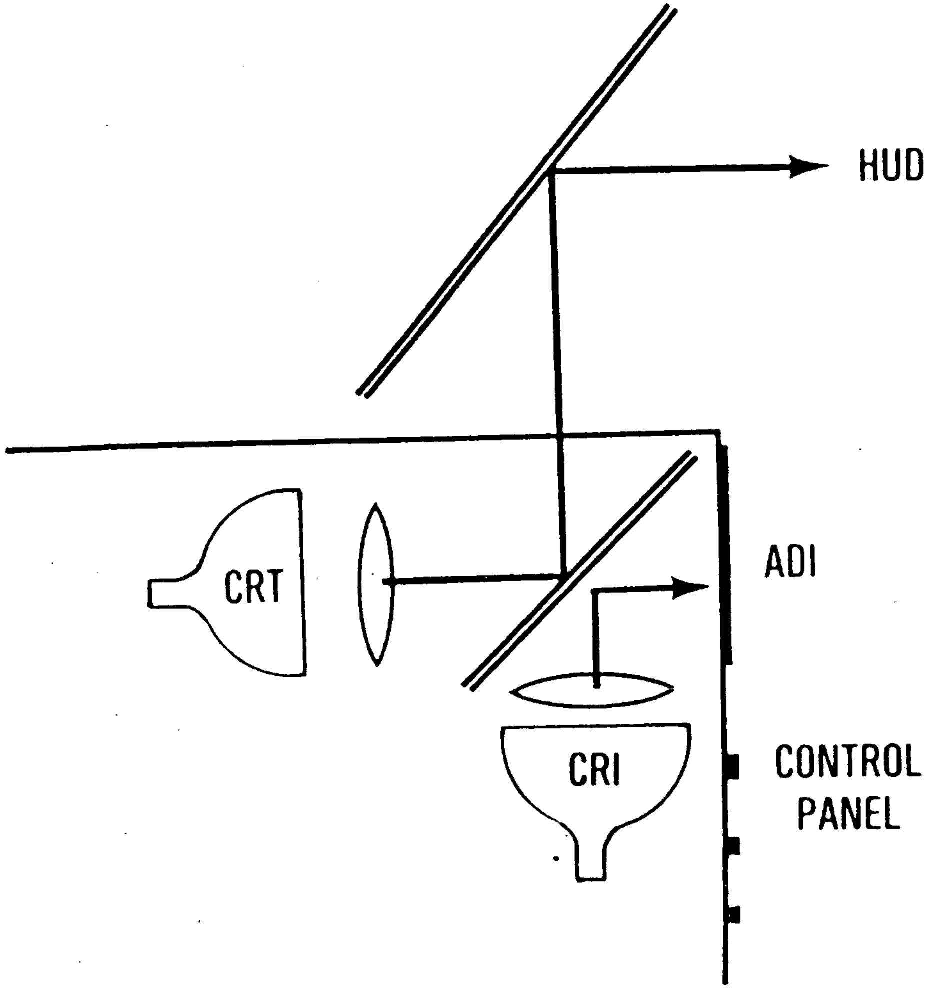
TWO COLOR CRT WITH HOLOGRAPHIC FOLD MIRROR



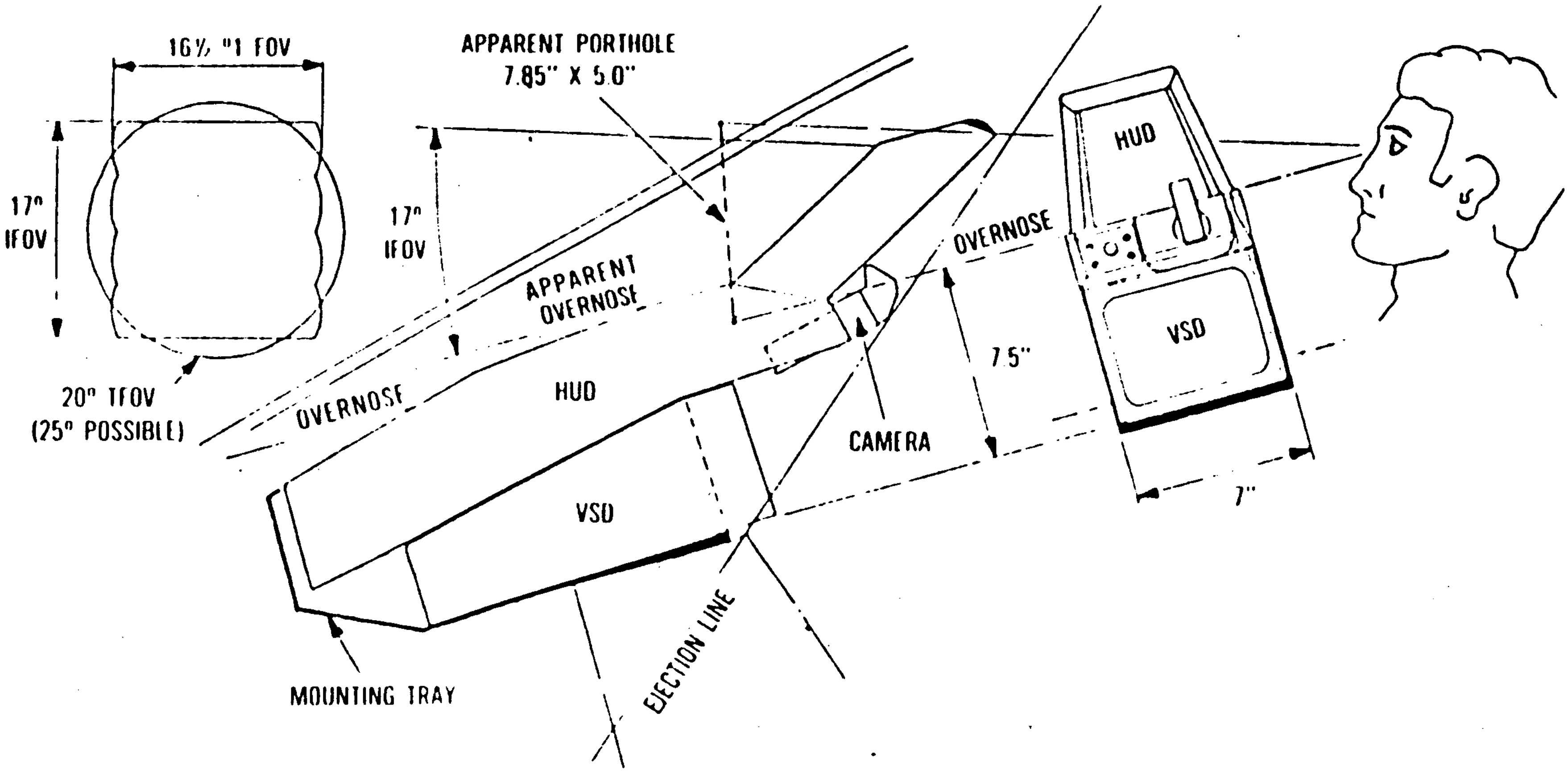
Viewgraph 13

3-6-16

USE TWO FOLD MIRRORS, TWO CRTS



LOW PROFILE HUDS: GEC MULTI-COMBINER HUD



ATTITUDE DISPLAYS FROM THE PERSPECTIVE OF AN ENGINEERING EXPERIMENTAL TEST PILOT

Mr. Joe Bill Dryden
General Dynamics, Ft Worth, Texas

BIOGRAPHY

My flying background includes over 8000 hours in F-100, F-104, F-105, F-106, F-4, F-15, F-16, YF-17, and F-16XL, in addition to civilian light aircraft and gliders. I have instructed both civilian and military; am a graduate of the F-4 Fighter Weapons School and Interceptor Weapons School, and was a project pilot on the Lightweight Fighter Flyoff. Though not a formal graduate of the USAF Test Pilot School, I flew in the flight test programs long enough at Edwards to have acquired that background by osmosis.

I was happy to see this conference called because in reading all the flying safety material, it's apparent we had this perceived spatial disorientation problem in the F-15, F-16 and any kind of modern fighter. My first impression was a little bit of disbelief--"not in my airplane"--and let me head off thoughts of "lying, cheating contractor." I've flown the aircraft since 1974, and most of my opinions and observations about the aircraft developed while flying it in the Air Force, and my opinion has not been substantially changed since moving to GD.

My initial impression was that I didn't believe it, but it's hard to ignore the numbers of guys who've obviously busted their ass from spatial disorientation. I was hoping to get together and come up with some solutions for this.

The reason I felt compelled to get up and talk was I felt we'd somehow lost sight of that. We've got a great knowledge base here. I've learned a lot about perceptions and what goes on when you're flying the airplane. Contrary to what Dave Milam says, I'd like to think I can go both modes regarding consciousness: I can click on consciousness and discuss what I'm doing with someone or what I'd like to see in the airplane.

We've got a lot of information about what's going on in research, but I'd like to caution everyone that it's conceptual now and you can concept the hell out of things but concepts are free, until you sit down and try to mechanize something. I'm recently at cross purposes with Artificial Intelligence People--Pilots Associate with how much authority I'm going to give the machine--harkening back to "Space Odyssey, 2001." I can just imagine crossing a ridgeline, spotting a MIG-23 at my left 10 o'clock and say, "Missile," and the airplane comes back with "Say Again," or worse yet, "Are we sure he's hostile?" Pilots given authority to fly airplanes are going to demand authority to employ its weapons.

They're going to want hands on, click-click control when they're either flying the machine or employing its weapons.

One promising area for audio warnings would be for SAM alert. I'd like to have RWR gear talk to me in terms of quadrants--a great area to use voice feedback.

But getting back to my main point, in the short term, what can we do to preclude this wastage because pilots don't perceive what's going on? I've heard training mentioned repeatedly here and I think that's an area we can do something about. We do not train people to cope with an environment they're not genetically equipped to cope with. Regarding our perceptions, hearing is one sense that most likely deteriorates with exposure to the noisy environment of jet engines and rock 'n roll.

If we don't train adequately, I feel it's criminal negligence. Too many Wing Commanders are so interested in making Pope below-the-zone that they're spring-loaded to avoid allowing anything, any situation that might involve the loss of an airplane. So all you accomplish is take this guy who's not prepared genetically to do so and put off the accident until he's in an extremely expensive airplane, or worse yet, in a combat situation where he's going to let his wingman, flight, squadron or country down because he cannot accomplish the mission. So what can we do in the meantime? We can train these people. I can just see the bean counters protesting, "My God, where's the money going to come from?" The maintainers are going to say, "How can we generate the sorties?" And the ops guys'll say, "Where are we going to find pilots to do the training?"

I realize it's not going to be easy, but we'd better do it soon or we'll be out of airplanes before we ever get these great systems we've been discussing the past few days on them.

We must realize what the limitations are, pressure people while they're being trained, and get serious about realistic training. We need to increase the number of sorties. I can't adequately train a guy to handle IMC unless I put him in actual IMC, task load him and force him to maintain some semblance of control. And if you don't, he's not going to be able to accomplish it.

Even if you took a pilot with the brain capacity of Albert Einstein and hand-eye coordination of Mary Lou Retton, and put him in an F-16 at Hahn, at night in the weather for the first time, without proper training, he'd bust his ass. Pure and simple. Regardless of enthusiasm and aircraft equipment, if you haven't developed the basic skills, you can't do it. Dave Milam was absolutely right: "Top spin forehand, top spin forehand, top spin forehand; attitude, airspeed, attitude, airspeed." It's got to be done enough in certain areas to overcome our limitations.

What can we do with the present systems? I know this is controversial, but I think we should use HUDs more today. I've flown the F-16 about 900 hrs and have not consciously looked heads down more than 30 minutes, and then mainly to the TACAN. We should be training more to use HUDs. The T-46 has only steam gauges. It's ludicrous to use that to train for HUD equipped aircraft.

HUDs can be improved greatly and I really liked the virtual imagery stuff we've seen--God, I love it. But it's still concept and I'll be long dead and gone before seeing it in an aircraft I can use. The HUD provides both a control and performance instrument right there if I utilize it right.

Discussing the inside-out/outside-in controversy, in using the ADI, by a simple change of mindset, I can go either way.

By rotating the airplane about the horizon, I'm going outside-in; if I think about tilting the horizon, I'm inside-out. And if I carry that a step further and look at the flight path vector outside-in, it works very well.

What is the flight path vector? It's simply where the CG of the airplane is going. To derive that in the INS or directly, I can say "pitch attitude plus or minus angle of attack." I've got wind and beta in there too but can deselect that if I want.

There's a different technique used in controlling the aircraft. If I try to control the aircraft on the HUD, using the velocity vector, like I do the ADI, it doesn't work that well. You also have the problem of what size corrections are necessary; the apparent size of corrections on the HUD are considerably larger than on the ADI because of the number of degrees in the field of view and because of focal length differences: the ADI's at about 40 inches; the HUD's focused at infinity, and though a degree's a degree, looking at a degree at infinity, it's much larger than at 25-40 inches.

Initially, the new guy has no concept about what size corrections to make. Again, this can be trained, as in learning to track a target on the HUD. Pulling too quickly results in an overshoot, so you learn to stop your pull based on rate and let the velocity vector drift up. You develop your own gains. If my target is 10°, I might pull it quickly to 6° or 7° and let it drift up; or I might pull it slowly to 9°, then let it drift up. So there's a definite technique involved. That flight path marker is great because it organizes so much information for you. If it's above the horizon, I'm going up, or if below, down. I don't have to make a change on the ADI, then check the vertical velocity, airspeed and altitude. It's all right there in front of me. I realize this is heresy to this group, but that's what we have right now, so let's teach 'em to use it.

Now, what can we do to reduce the number of accidents? And I realize it's not a simple task just to increase the training. The complexity of the problem is almost insurmountable and I hope we'd make it less so. Unless he's been prepared, actually flown real airplanes in real weather, with the distractions attending to it, been told what the perceptual process is and the limitations of his equipment, unless he's been told "I have to mentally suppress the peripheral vision because in the weather it frequently lies to me, and I have to be able to look at things directly, especially the HUD," he'll have problems. If I'm serious about precise aircraft control, I have to look at the ADI. After sufficient training in a variety of demanding conditions, he comes up with his own set of rules and a personal technique that works for him, regardless of the flight conditions: Weather, lightening, low light level, in and out of clouds; what can I trust, what can I not trust. What do I learn to ignore, what do I learn to evaluate, and either use or not use depending upon the conditions I've been preconditioned to with the luxury of an IP in the back seat, or right next to me, to where I don't make a fatal error.

DISCUSSION

Dr. R. M. Taylor: What improvements would you make to HUDs right now?

JBD: One thing is to extend the horizon line across the face of the combiner.

Dr. Gerald Gard; Kaiser: You can extend the horizon line, in fact overlay it on everything else.

JBD: I didn't like the idea that you can't extrapolate from the HUD because it's only 10° X 16° versus the ADI which is 110° X 110°. I mentally extend the horizon widely when flying in the weather. It's a mental process; how? Practice, practice, practice. In order to see the velocity vector and part of the pitch ladder, I may have to bob and weave my head a bit, but I know it's all there. We could also improve the alphanumerics for faster recognition. There are some analog displays that have a lot of merit for either up or down. There are many things we could improve. But now we need to train with what we have. We don't even let guys fly with the ADI in actual weather. But we've got to do one or the other.

Dr. William Richardson: With the majority of HUDs in single seat aircraft, do we have an opportunity to train unusual attitude recovery by the HUD?

JBD: You should use two seaters. Recently, I covered all instruments and flew the front seat via only the HUD, having the back seater present me one unusual attitude after another, for 1:20. Had no problem. If the pitch lines were solid, going up; if hatched, going down; numbers upright, I'm upright; numbers inverted, so am I. It's not that difficult. Of course, I was alerted to expect unusual attitudes. Also, prevention is important. If he knows the environment he's in, hopefully he won't permit himself to enter that unusual attitude in the first place. They should never have to recover from 90o straight up or down without a clue as to what's going on. Training is also important in teaching pilots how to budget their time. If I'm cross-country, and need to change destination, I check attitude, map case, attitude, get map, attitude, check heading, attitude, get letdown book, attitude, find letdown plate, attitude, check plate and altitude, read plate, attitude--it's got to be done that way. The more experienced guys may spend less time on attitude, but the younger guys need denote a greater percentage of their time on attitude. By the simple expedient of the L-COS (Lead-Computing Optical Sight), I can teach use of the HUD.

Lt Col William Ercoline: We don't know if we've got the equipment to teach this, or if the HUD's capable, but the real question is, do we have a system that supports what you want to do?

JBD: No. Need to seek out weather, though I realize the T-38's not designed for weather. Also need IPs that know how to fly in weather and to teach it. I suspect only 5 percent of the present IP force is really qualified. That's a training problem, too. The alternative is seeing expensive aircraft scattered over landscape because we haven't taught guys to do 'em. If you don't occasionally lose a T-37 in training, probably not doing it right.

Paul Pencikowsky, Northrup: Our emotional reaction to these issues shows we all have a different perception of the problem. The problem breaks down to three possibilities: (1) HUDs don't work, the symbol set is inadequate; (2) HUDs work, the symbol set's okay, but the training is deficient; or (3) it is possible that there is negative transfer coming off the ADI. So step one is to define the nature of the problem. Take a virgin group of 24 and have them fly only HUD-equipped T-37 or T-38, then test them, comparing them with pilots growing up on the ADI. Until you do that, you haven't defined the problem--only theories.

JBD: I understand you need a statistically valid sample to do this, but I contend that they're not getting enough of either ADI or HUD.

Unidentified: When you described your HUD recovery technique, you stepped us through a series of conscious cognitive processes, not an automatic subconscious process (implying that JBD's technique is more time-consuming than recovery by means of an ADI).

JBD: No argument with that. But if you think for one minute that the recovery from an unusual attitude is automatic using the ADI, you have no idea what goes on in the cockpit. For you to do any contolling on the aircraft with an ADI, you must "LOOK" at the ADI just like you do with the HUD.

Col Grant McNaughton: But with the ADI, recognition of an unusual attitude is instantaneous; no time is lost in cognitive processing. Furthermore, the dynamics of the ADI are sufficiently slow so as to permit easier recognition of pitch and roll and to speed up the correct response. To cope with rapid pitch or roll rates on the HUD, you must first stop the pitch or roll rate so you can interpret the HUD. The HUD's a great display for many things but not for the recognition of or coping with unexpected unusual attitudes.

AIRCRAFT ATTITUDE AWARENESS WORKSHOP
Thursday Afternoon Open Forum Session
10 October 1985

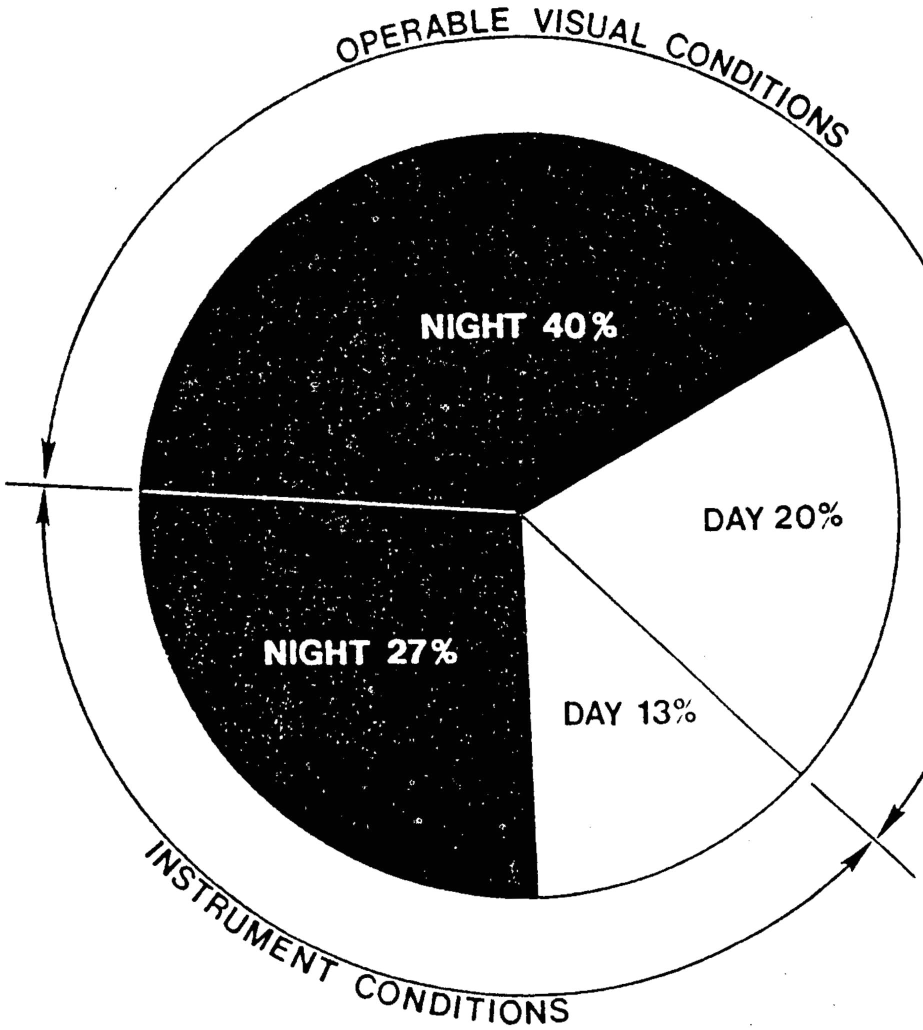
(Ed. Note: Unfortunately, the quality of the recording of certain segments of this session was marginal or undecipherable. Where the exact wording was not decipherable, the general gist is reconstructed insofar as possible. Hopefully, the speaker's intended meaning has been preserved. Speakers were identified wherever possible. Unfortunately, many sitting at a distance from the recorder were not well-recorded nor identified.)

Col McNaughton: I'd like to focus on a couple of aspects; namely, what can we do to improve the immediate problem. To kick this session off, I'd like Maj Gary Morphew, HQ AFISC/SEFF, an F-4 pilot with 4000 hours plus strong interest in human factors, to provide a safety perspective.

Maj Morphew: I called AFISC over the noon hour for data since 1980, Class A mishaps, which involved spatial disorientation (SDO), (meaning there was some attempt to fly the aircraft out of the situation by looking at instruments and trying to recover, but hit the ground anyway), versus controlled Flight Into Terrain (CFIT) where the guy isn't looking forward; he's just not monitoring his flight path at all and he hits the ground. Just so we know where the problem is, SDO we've had 19, CFIT 54. I'm allowing 10 percent for coding errors because I haven't had a chance to look at the raw data myself. There's a significant difference as to where the problem lies. That means we can form better opinions where our problems are. No one will disagree with a lack of training and getting better displays, but if the pilot is unaware of the situation, he can't very well use the best information we can provide him on the HUD, ADI or whatever.

Col McNaughton: If I could take a few minutes to reiterate the problem as I see it:

- First, why do we train in disorienting conditions? Well, we may have to fight there. This vugraph from Marconi (Fig 1) shows that during a typical 24-hour period in Central Europe in the wintertime, 40 percent is IMC.
- From AFISC, types of aircraft experiencing loss of aircraft attitude awareness in our fighters: A-7 and A-10 both collide with the surface because that's where they fly.
- The A-10 has a big problem with the inadvertent over-bank-descent, partly because of basic misleading aircraft features: angled canopy rail and stubby nose which denies the pilot a rapid cue to pitch and turn. The A-10 is highly maneuverable but under-powered. It's easy



FLYING CONDITIONS - CENTRAL EUROPE
WINTER - TYPICAL 24 HR. PERIOD

Figure 1

to rack it up to high bank angles--but if the thrust is insufficient to maintain level flight, it will fly a descending flight path, and with the lack of nose, it may not register early enough.

- There are lots of aircraft that don't have a canted canopy rail. In the old days, designers included a relatively long nose as well as a relatively level canopy rail (which provide a cue to the horizontal): including the T-6, T-28, T-33, T-37, F-84, F-5, F-84F, F-86, F-100, and F-105. A-10, A-7, F-106 and F-4 all have canted rails (Fig 2).

The impact of SDO on the AF fighters as a percentage of ops factor mishaps is as follows: A-7, A-10 and F-5 clump around 10 percent whereas the F-4 and F-15 are at 20 percent and the F-16 is at 30 percent. Common denominators in the latter aircraft include large HUD control panels that drive the ADI down deep in the instrument panel. Note the F-5 with the big ADI high in the center of the instrument panel (Fig 3) and note what happens when they put a HUD in it--it's smaller and deeper (Fig 4). We need a HUD equipped T-38 but realize what happens to the primary attitude reference. Note the A-7--big ADI high in center immediately below a small HUD control panel (Fig 5)--that's a good design and their low SDO rate reflects that. Same with the A-10 (Fig 6). One other thing about the A-7 is that the high peaked instrument panel makes it easy to come back inside without even seeing ahead--one reason why they can easily fly into the ground. Same to some extent with the A-10. A recent A-7 mishap occurred day VFR coming off the range; the pilot checked over his shoulder for BDA, snap glanced inside to check fuel (lower right of instrument panel), and only moments later realized he was flying into the trees. An A-10 pilot flying a low level 180o turn to trail his leader padlocked his sight on the leader who was above and to his right and failed to realize he was descending. Fortunately, the range control officer called an altimeter setting. This pilot snapped his eyes to the altimeter, then looked up and saw, very clearly, the point on the ground beyond two trees that he was going to impact. He pulled to the peak performance tones, hit the trees, but was able to nurse the plane home. There's a tradeoff in design between tugging eyes outside like the F-16, or inside like many other aircraft. Pilots need to be aware of the difference.

In the F-15 (Fig 7), the ADI is over 35° below the design eye line--due to the instrument stack which includes the radio, transponder and HUD control panel. To keep the ADI in view while flying formation requires that the wingman stack further back such that his wing overlaps lead's horizontal stab and affects lead's "feel."

In the F-16 (Fig 8), the ADI is over 30° below the design eye line. Because of the roomy canopy, pilots commonly sit with their eyes as much as 2" above the design eye line, effectively making the ADI even deeper. And the F-16 ADI is small--the horizon is less than 2" in diameter, and it is far away - 24-32" from the eye depending on seat adjustment so it does not subtend as

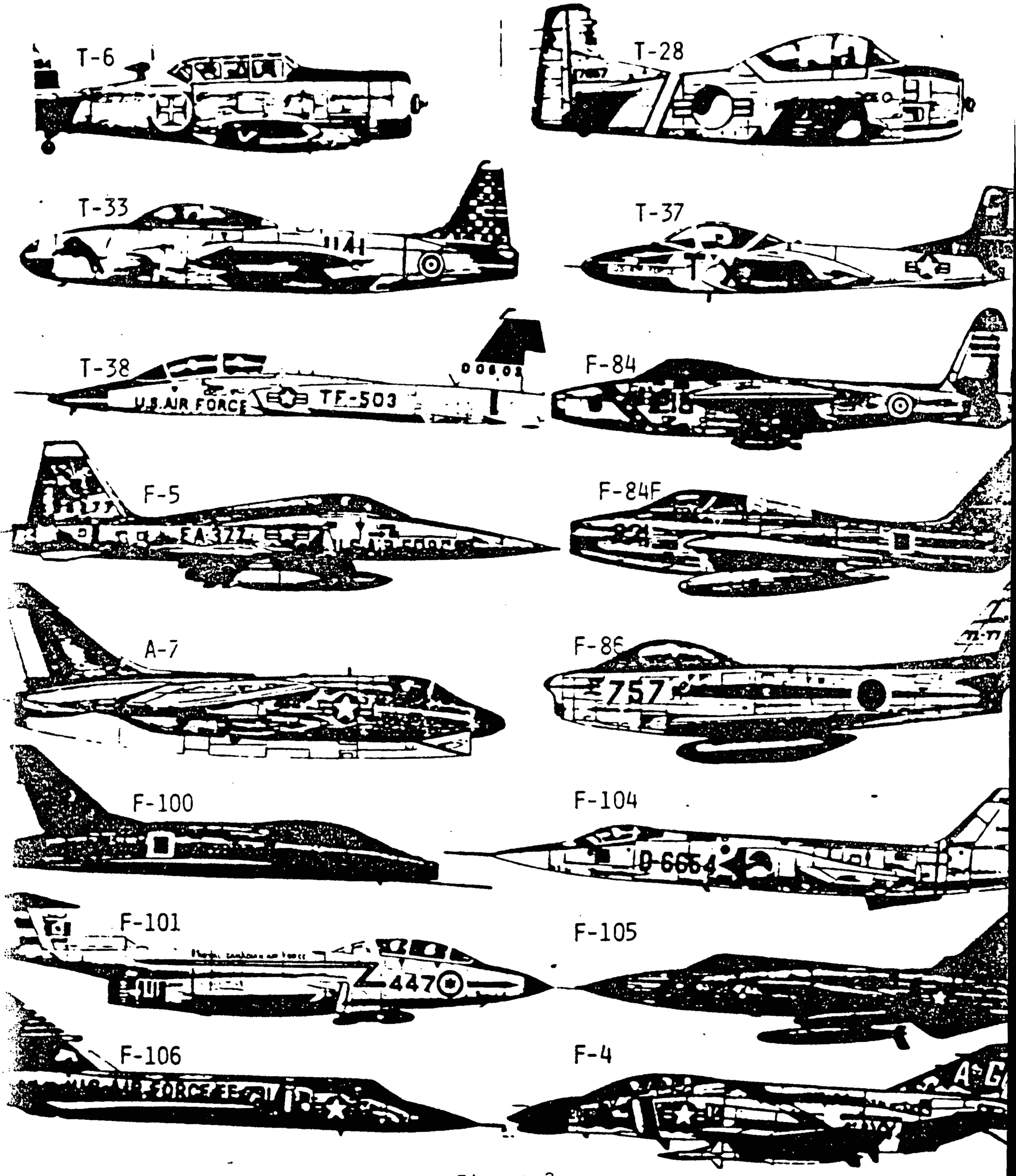
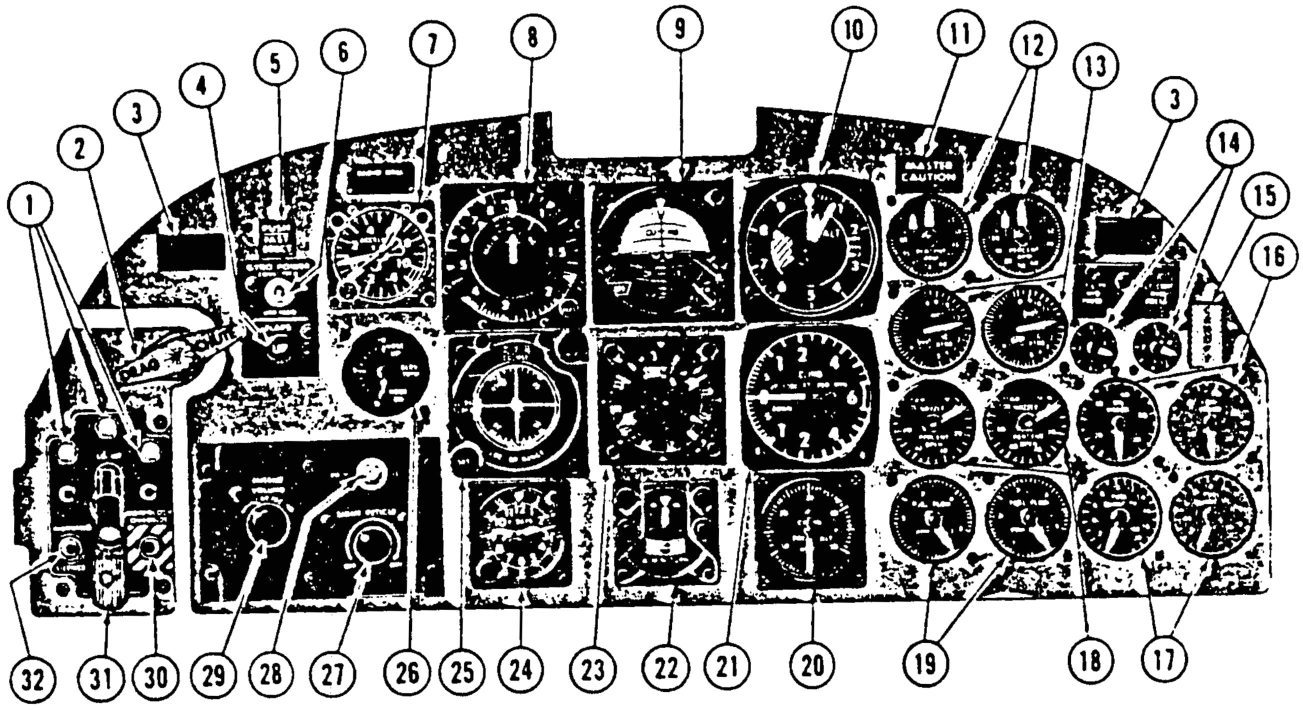
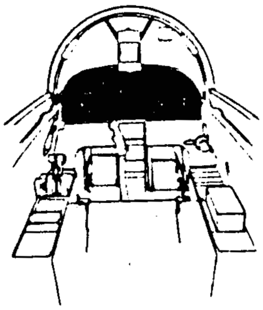

T-6
T-28
T-33
T-37
T-38
U.S. AIR FORCE
TF-503
F-84
F-5
F-84F
A-7
F-86
757
F-100
F-104
F-101
447
F-105
F-106
F-4

Figure 2

INSTRUMENT PANEL (TYPICAL)

A RF



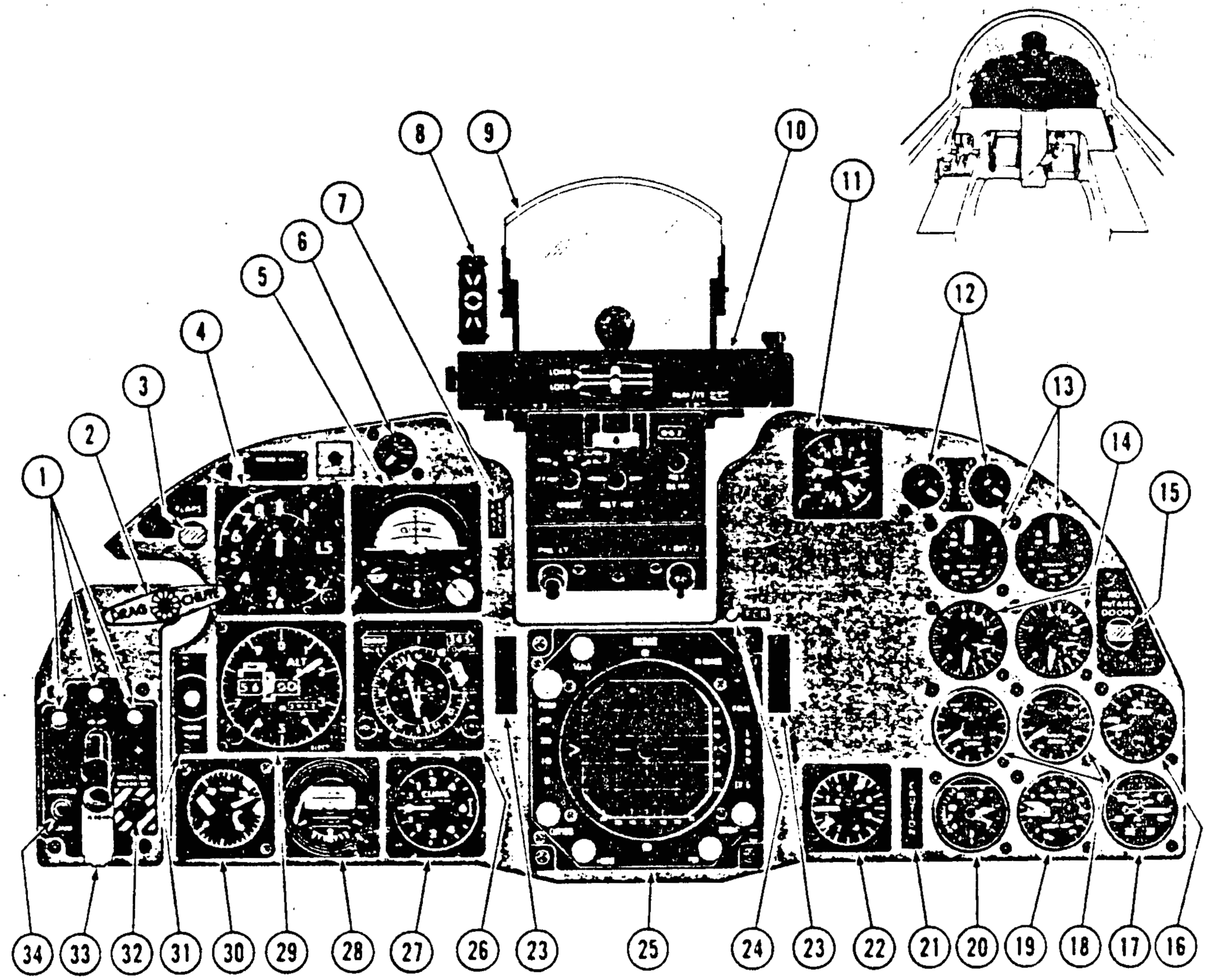


1 LANDING GEAR POSITION INDICATOR LIGHTS
2 DRAG CHUTE T-HANDLE
3 ENGINE FIRE WARNING LIGHT
4 FLAP POSITION INDICATOR
5 ATTITUDE INDICATOR FAST ERECT. SWITCH
6 GYRO POWER SWITCH
7 ACCELEROMETER
8 AIRSPEED-MACH INDICATOR
9 ATTITUDE INDICATOR
10 ALTIMETER
11 MASTER CAUTION LIGHT
12 ENGINE TACHOMETER INDICATORS
13 EXHAUST GAS TEMPERATURE INDICATORS
14 HYDRAULIC PRESSURE INDICATORS
15 CANOPY UNLOCKED WARNING LIGHT
16 OIL PRESSURE INDICATORS
17 FUEL QUANTITY INDICATORS
18 NOZZLE POSITION INDICATORS
19 FUEL FLOW INDICATORS
20 CABIN ALTIMETER
21 VERTICAL VELOCITY INDICATOR
22 TURN AND SLIP INDICATOR
23 BEARING-DISTANCE-HEADING INDICATOR
24 CLOCK
25 COURSE INDICATOR
26 HORIZONTAL TRIM INDICATOR
27 SIGHT RETICLE BRIGHTNESS CONTROL KNOB
28 SIGHT FILAMENT SELECTOR SWITCH
29 MISSILE VOLUME CONTROL KNOB
30 DOWNLOCK OVERRIDE BUTTON
31 LANDING GEAR LEVER
32 LANDING GEAR WARNING SILENCE BUTTON

Figure 3

INSTRUMENT PANEL-FRONT

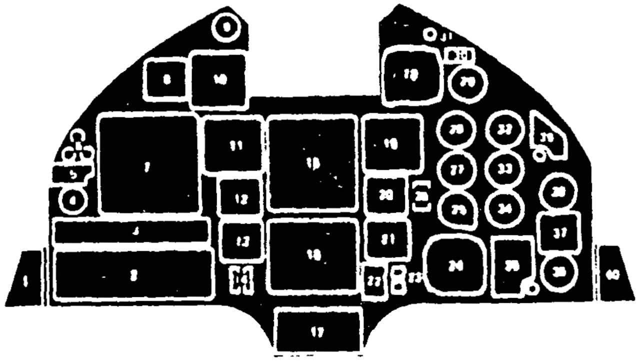
F-1 **F-2**

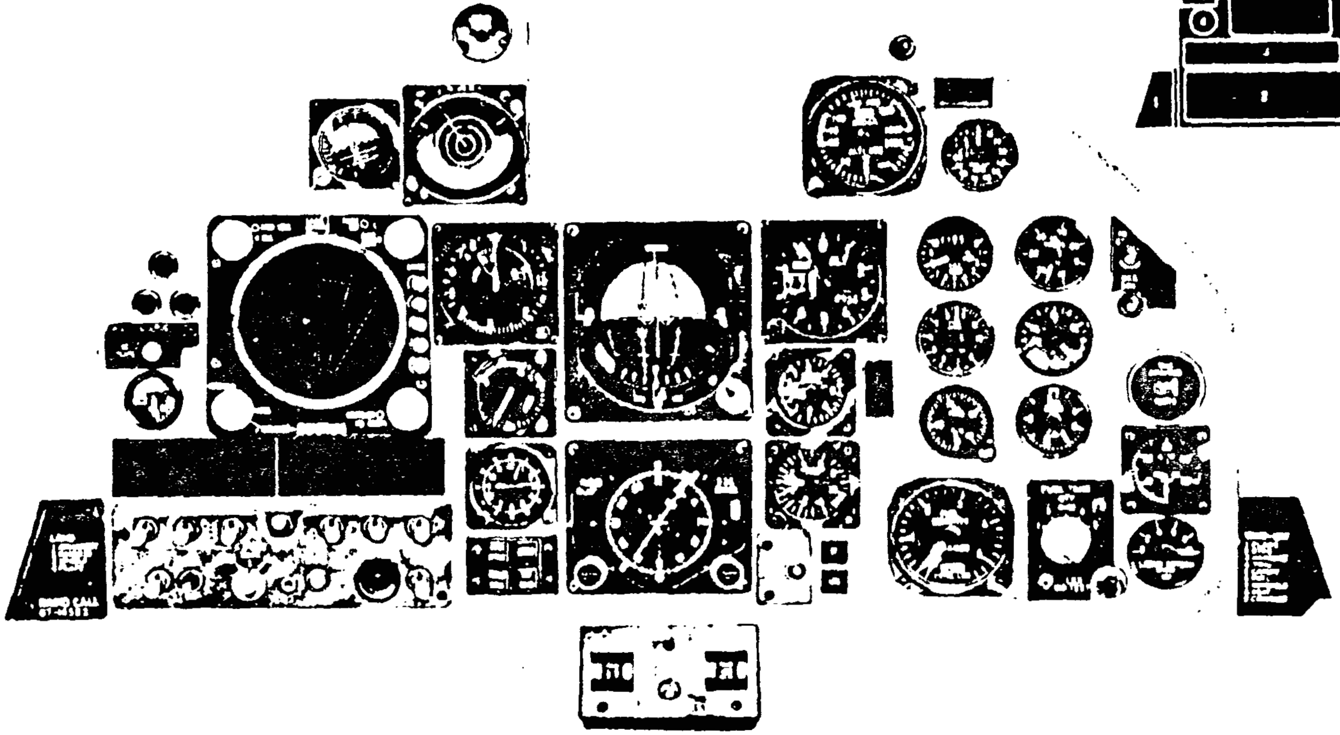


1	LANDING GEAR POSITION INDICATOR LIGHTS
2	DRAG CHUTE HANDLE
3	FLAP INDICATOR
4	AIRSPEED-MACH INDICATOR
5	ATTITUDE INDICATOR
6	PITCH TRIM INDICATOR
7	ATTITUDE INDICATOR FAST-ERECT SWITCH
8	ANGLE-OF-ATTACK INDEXER
9	COMPUTING OPTICAL SIGHT
10	SIGHT CAMERA
11	CLOCK
12	HYDRAULIC PRESSURE INDICATORS
13	ENGINE TACHOMETERS
14	EXHAUST GAS TEMPERATURE INDICATORS
15	AUXILIARY INTAKE DOORS INDICATOR
16	OIL PRESSURE INDICATOR (DUAL)
17	CABIN PRESSURE ALTIMETER
18	NOZZLE POSITION INDICATORS
19	FUEL QUANTITY INDICATOR (DUAL)
20	FUEL FLOW INDICATOR (DUAL)
21	MASTER CAUTION LIGHT
22	ACCELEROMETER
23	FIRE WARNING LIGHT
24	RADAR CONTROL INDICATOR LIGHT
25	RADAR INDICATOR
26	HORIZONTAL SITUATION INDICATOR
27	VERTICAL VELOCITY INDICATOR
28	STANDBY ATTITUDE INDICATOR
29	ALTIMETER
30	ANGLE-OF-ATTACK INDICATOR
31	ARRESTING HOOK BUTTON
32	LANDING GEAR DOWNLOCK OVERRIDE BUTTON
33	LANDING GEAR LEVER
34	LANDING GEAR AND FLAP WARNING SILENCE BUTTON

Figure 4

INSTRUMENT PANEL (TYPICAL) → [26]





1. LAND checklist
2. ARMT select panel
3. Armament advisory light panel
4. Flap position indicator
5. LE FLAPS indicator
6. LG POS lights (3)
7. Forward looking radar
8. Standby attitude indicator
9. Speed brake indicator
10. APR-36 threat analyzer
11. Mach-airspeed indicator
12. Angle-of-attack indicator
13. Clock
14. Attack master function switches (4)
15. Attitude director indicator
16. Horizontal situation indicator
17. ARMAMENT RELEASE panel
18. Radar altimeter
19. Barometric altimeter
20. Vertical velocity indicator
21. Accelerometer
22. HDG MODE switch
23. TF and LDG master function switches
24. Fuel quantity indicator
25. Turbine outlet pressure indicator
26. MASTER CAUTION light
27. Fuel flow indicator
28. Turbine outlet temperature indicator
29. Tachometer
30. FIRE warning light
31. Fire warning switch
32. Oil pressure indicator
33. Oil quantity indicator
34. Hydraulic pressure indicator
35. FUEL TANK QTY selector
36. LIQUID OXYGEN indicator
37. Cockpit pressure altimeter
38. TRUE AIRSPEED indicator
39. MKR BCN, LOW ALT lights
40. TAKE OFF checklist

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Figure 5

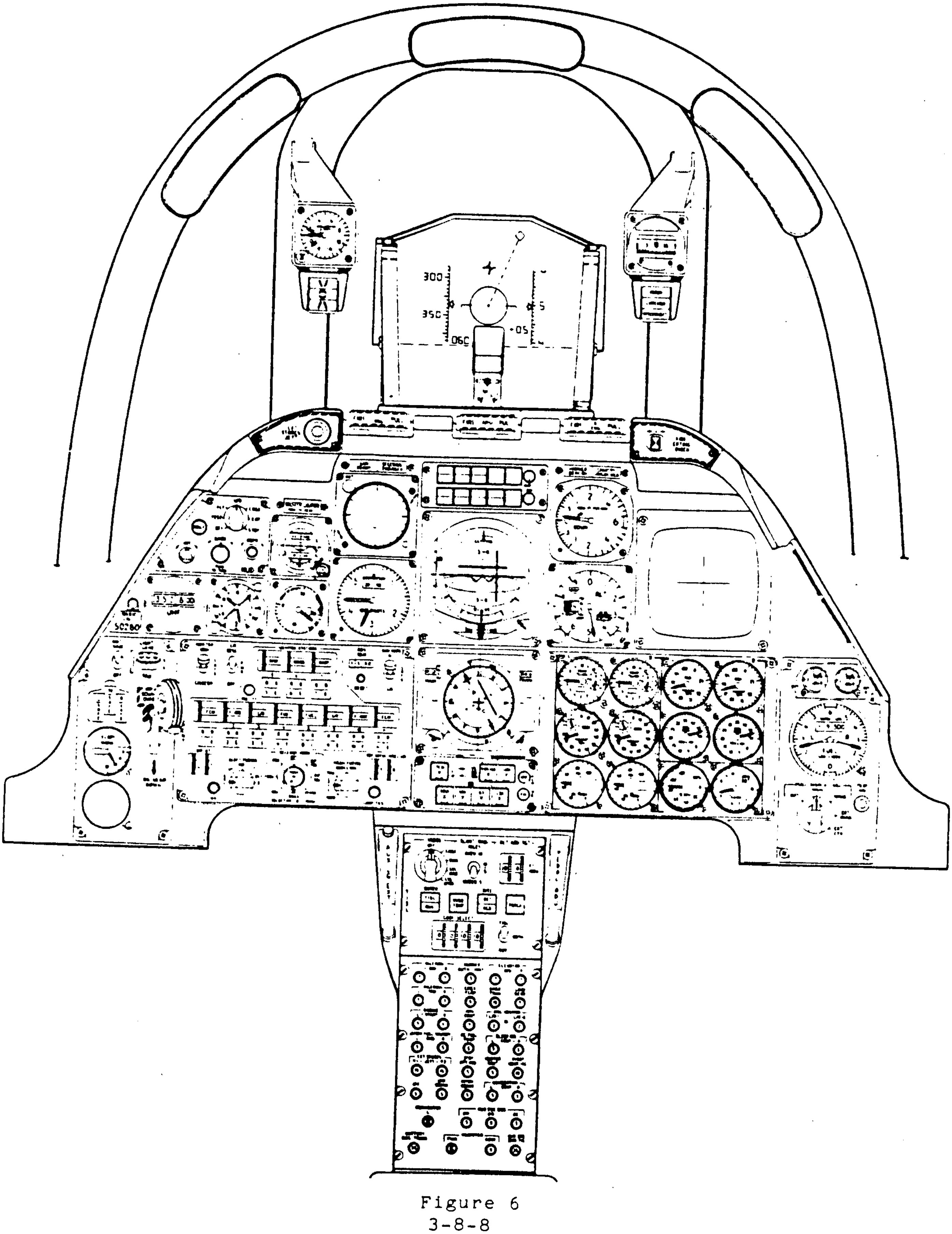
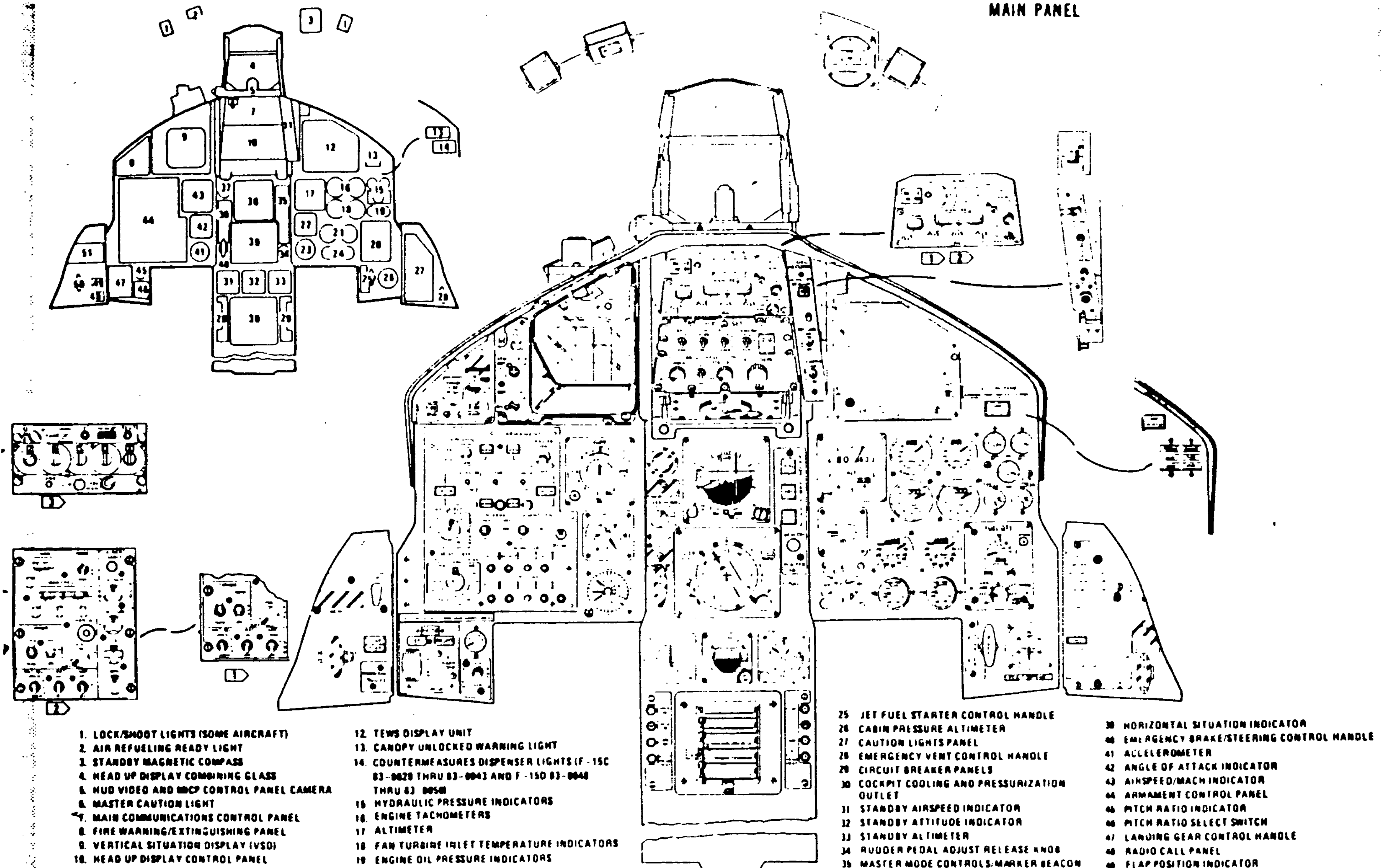


Figure 6

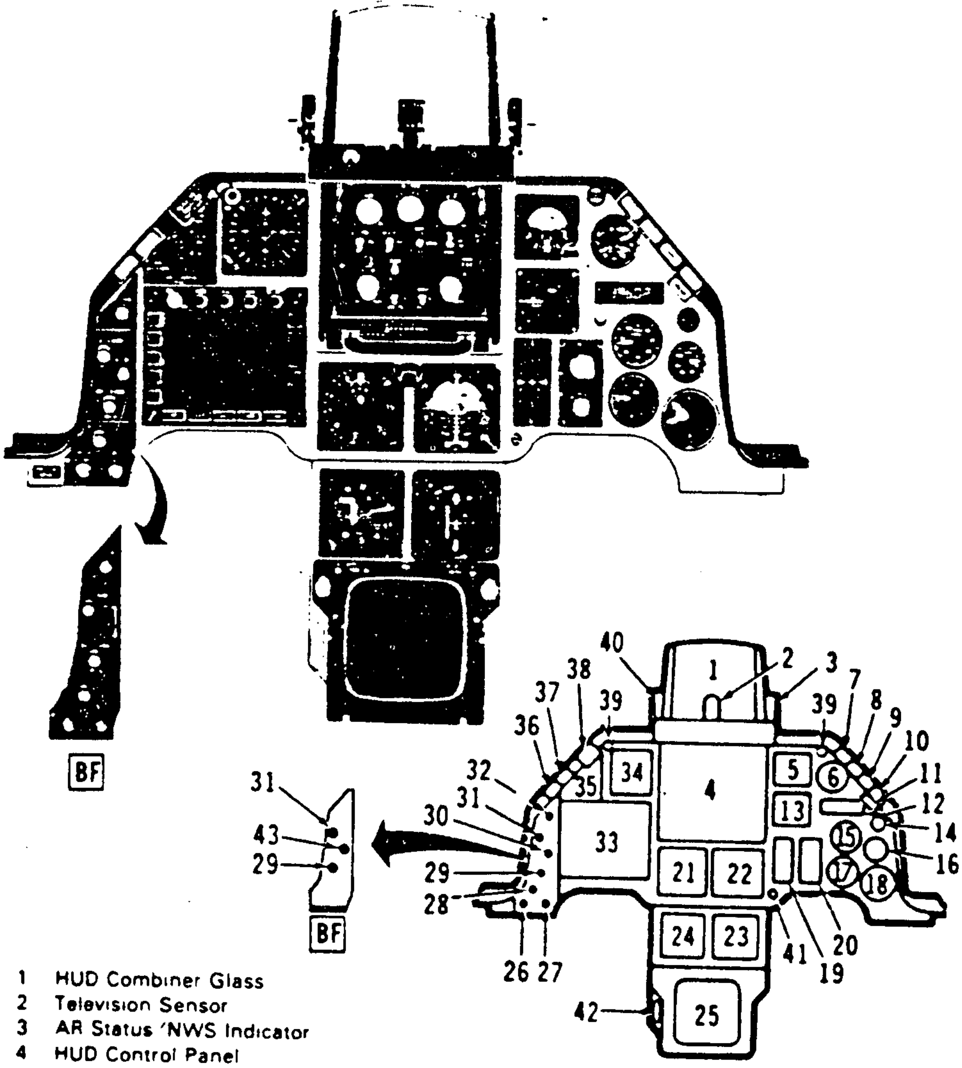


1. LOCK/SHOOT LIGHTS (SOME AIRCRAFT)
2. AIR REFUELING READY LIGHT
3. STANDBY MAGNETIC COMPASS
4. HEAD UP DISPLAY COMBINING GLASS
5. HUD VIDEO AND MCP CONTROL PANEL CAMERA
6. MASTER CAUTION LIGHT
7. MAIN COMMUNICATIONS CONTROL PANEL
8. FIRE WARNING/EXTINGUISHING PANEL
9. VERTICAL SITUATION DISPLAY (VSD)
10. HEAD UP DISPLAY CONTROL PANEL
11. VIDEO TAPE RECORDER CONTROL PANEL,
    AFTER TO-15 017
    GUN SIGHT CAMERA CONTROL PANEL,
    BEFORE TO-15-017
12. TEWS DISPLAY UNIT
13. CANOPY UNLOCKED WARNING LIGHT
14. COUNTERMEASURES DISPENSER LIGHTS (F-15C 83-0028 THRU 83-0043 AND F-15D 83-0048 THRU 83 0050)
15. HYDRAULIC PRESSURE INDICATORS
16. ENGINE TACHOMETERS
17. ALTIMETER
18. FAN TURBINE INLET TEMPERATURE INDICATORS
19. ENGINE OIL PRESSURE INDICATORS
20. FUEL QUANTITY INDICATOR
21. ENGINE FUEL FLOW INDICATORS
22. VERTICAL VELOCITY INDICATOR
23. EIGHT DAY CLOCK
24. ENGINE EXHAUST NOZZLE POSITION INDICATORS
25. JET FUEL STARTER CONTROL HANDLE
26. CABIN PRESSURE ALTIMETER
27. CAUTION LIGHTS PANEL
28. EMERGENCY VENT CONTROL HANDLE
29. CIRCUIT BREAKER PANELS
30. COCKPIT COOLING AND PRESSURIZATION OUTLET
31. STANDBY AIRSPEED INDICATOR
32. STANDBY ATTITUDE INDICATOR
33. STANDBY ALTIMETER
34. RUDDER PEDAL ADJUST RELEASE KNOB
35. MASTER MODE CONTROLS/MARKER BEACON PANEL
36. ATTITUDE DIRECTOR INDICATOR
37. EMERGENCY JETTISON BUTTON
38. STEERING MODE PANEL
39. HORIZONTAL SITUATION INDICATOR
40. EMERGENCY BRAKE/STEERING CONTROL HANDLE
41. ACCELEROMETER
42. ANGLE OF ATTACK INDICATOR
43. AIRSPEED/MACH INDICATOR
44. ARMAMENT CONTROL PANEL
45. PITCH RATIO INDICATOR
46. PITCH RATIO SELECT SWITCH
47. LANDING GEAR CONTROL HANDLE
48. RADIO CALL PANEL
49. FLAP POSITION INDICATOR
50. EMERGENCY LANDING GEAR HANDLE
51. ARRESTING HOOK CONTROL SWITCH

F-15

Figure 7

INSTRUMENT PANEL A BF



1 HUD Combiner Glass
2 Television Sensor
3 AR Status/NWS Indicator
4 HUD Control Panel
5 Standby Attitude Indicator
6 Fuel Flow Indicator
7 DUAL FC FAIL Warning Light (Red)
8 HYD/OIL PRESS Warning Light (Red)
9 CANOPY Warning Light (Red)
10 RDR ALT LOW Warning Light (Red)
11 ENGINE Warning Light (Red)
12 Radio Channel/Frequency Indicator
13 Vertical Velocity Indicator
14 Oil Pressure Indicator
15 RPM Indicator
16 Nozzle Position Indicator
17 FTIT Indicator
18 Fuel Quantity Indicator
19 AOA Indicator
20 Instrument Mode Select Panel
21 Airspeed Mach Indicator
22 Attitude Director Indicator
23 Horizontal Situation Indicator
24 Altimeter
25 Radar/EO Display
26 Autopilot PITCH Switch
27 Autopilot ROLL Switch
28 AUTOPILOT Switch
29 MASTER ARM Switch
30 ALT REL Button
31 LASER ARM Switch
32 IFF IDENT Button
33 Stores Control Panel
34 Threat Warning Azimuth Indicator
35 THREAT WARNING Controls and Indicators
36 ENG FIRE Warning Light (Red)
37. T.O./LAND CONFIG Warning Light (Red)
38. MASTER CAUTION Light (Amber)
39. Spotlight
40. AOA Indexer
41. MRK BCN Light
42. Rudder PEDAL ADJ Knob
43. BF OVRD Light

Figure 8

much a commanding angle at the eye. Then, under certain conditions of glare and reflections at night, the upper half of the ADI can appear to be a uniform gray color--leading the pilot to believing himself S&L when he's in a descent.

The small ADI problem is worse in more "state-of-the-art cockpits:" In the F-15E (Fig 9) and F-18 (Fig 10), it is even deeper - along the bottom of the instrument panel; and in the F-16C/D (Fig 11), it is even deeper than in the A/B. In the F-4 (Fig 12), the ADI is down relatively deep because of the radar scope.

HUD displays lack any uniformity from one aircraft to the next.

Again, a plea for the importance of the ADI: Full-time dedication, located high in the center of the instrument panel, to provide a constant attitude reference in a constant location to preclude having to call it up and hunt for it, to help maintain orientation and to facilitate coping with unexpected unusual attitudes and recognized SDO. Another reason to dedicate the ADI full-time is that the pilot may not always know ahead of time when he's going to need it - as in Col. Kehoe's case, or in the case of a pop-up, pull-down ordinance pass: during a series of these on the LANTIRN simulator, after pulling down and rolling upright again, I became so engrossed in getting the target that I forgot I'd rolled upright; nothing on the HUD told me differently; result is that on two of about 25 passes, I rolled invertical and crashed. The monitor said that "real fighter pilots" made the same mistake. That's why we need a big Primary Dedicated Attitude Display right below the HUD.

Bart Brooks, Hill AFB: Former T-37 IP. We can't change the F-16A/B. Don't have the money.

Col McNaughton: Bill Augustine and several of us feel there are some things we might do. One is to project an attitude display into the HUD control panel, thereby getting double use of it. One approach would be that of Garrett of Canada, represented here by Mr. Art Kennedy and Ray Taylor project a modified Malcolm Horizon onto the HUD control panel. It would either need a sky pointer or would need a multiple raster pattern to simulate the surface--to create, in effect, a contrast pattern between sky and surface.

Dick Malcolm himself came up with another idea: to cover the HUD control panel with holographic decals, then project an attitude display onto it. Tom Furness is funding Dick to perform a feasibility study of that concept right now. The idea is to be able to use the HUD control panel as a HUD control panel and as an attitude reference simultaneously, without any significant hardware change, other than adding an attitude projector to the right canopy rail.

F-15E Forward Cockpit

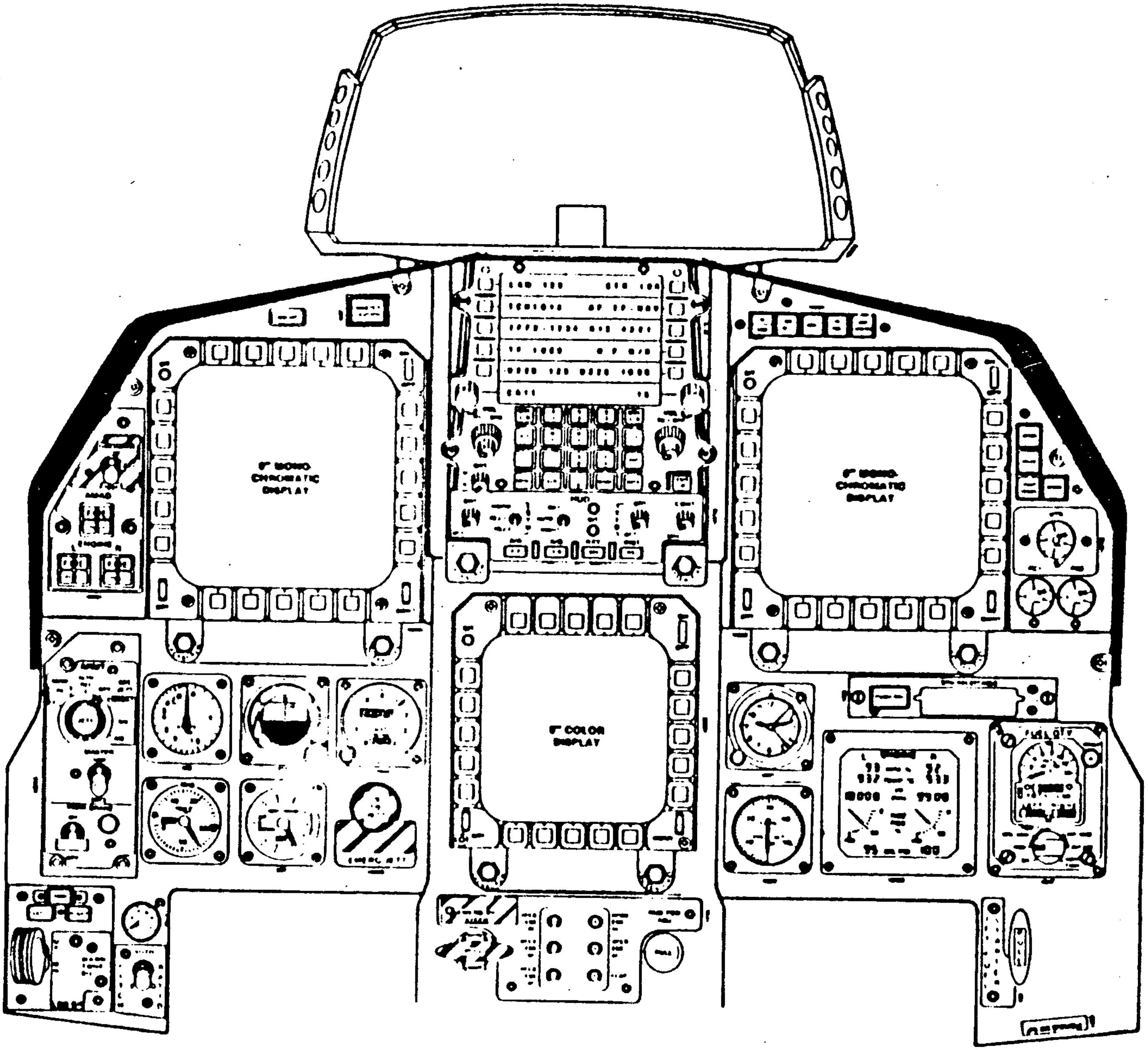


Figure 9

F/A-18 HORNET COCKPIT

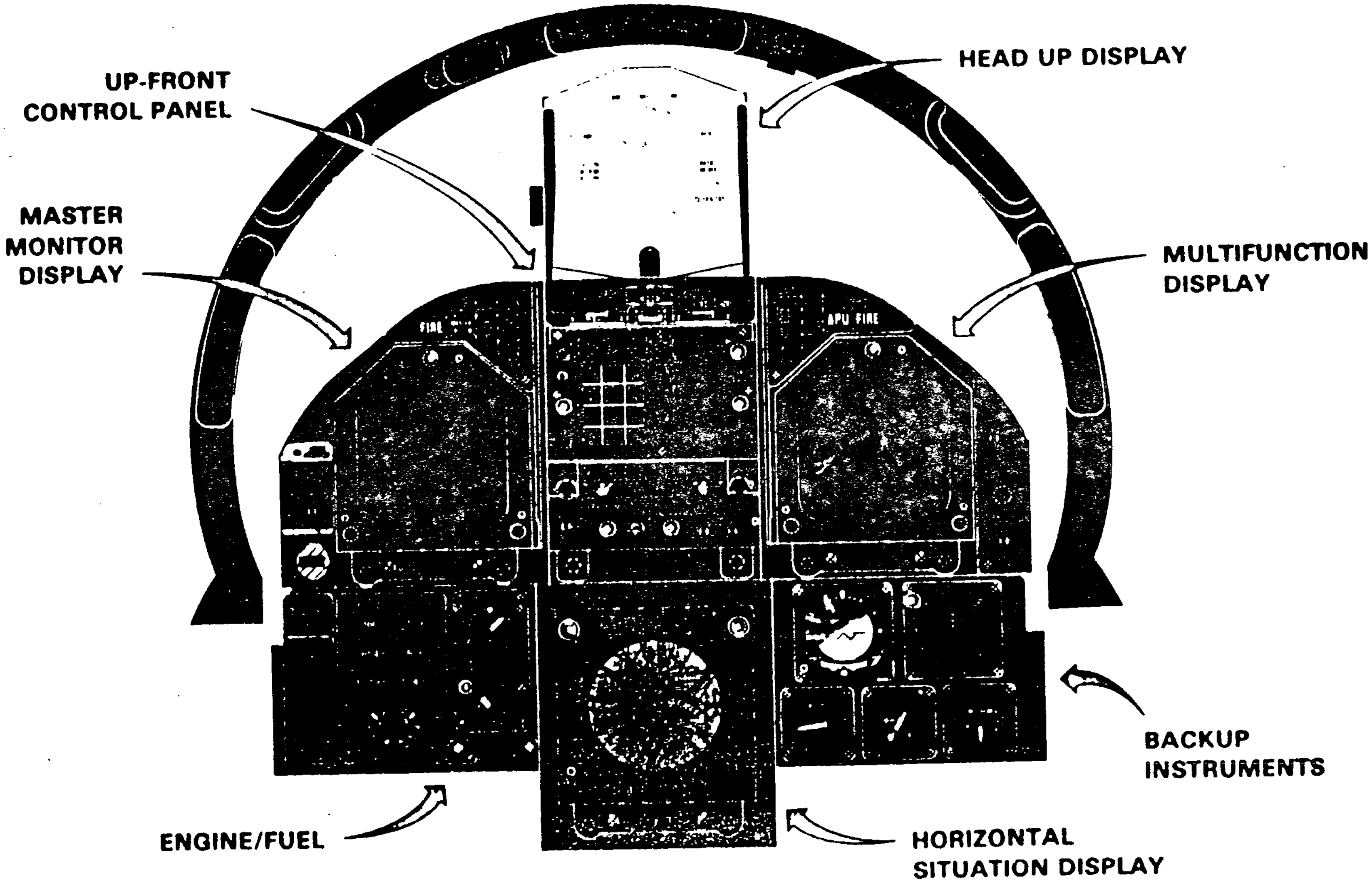


Figure 10A

MAIN INSTRUMENT PANEL

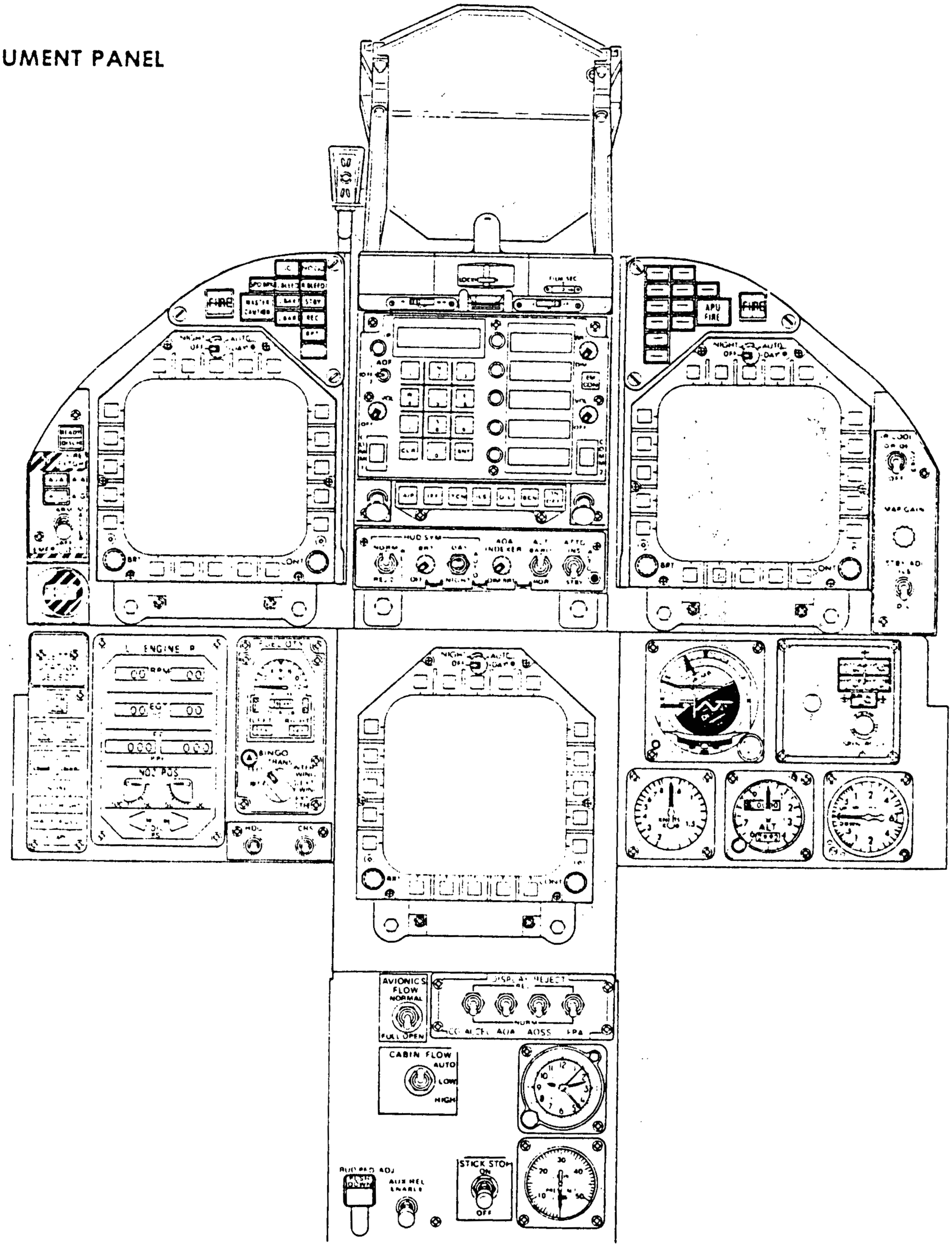
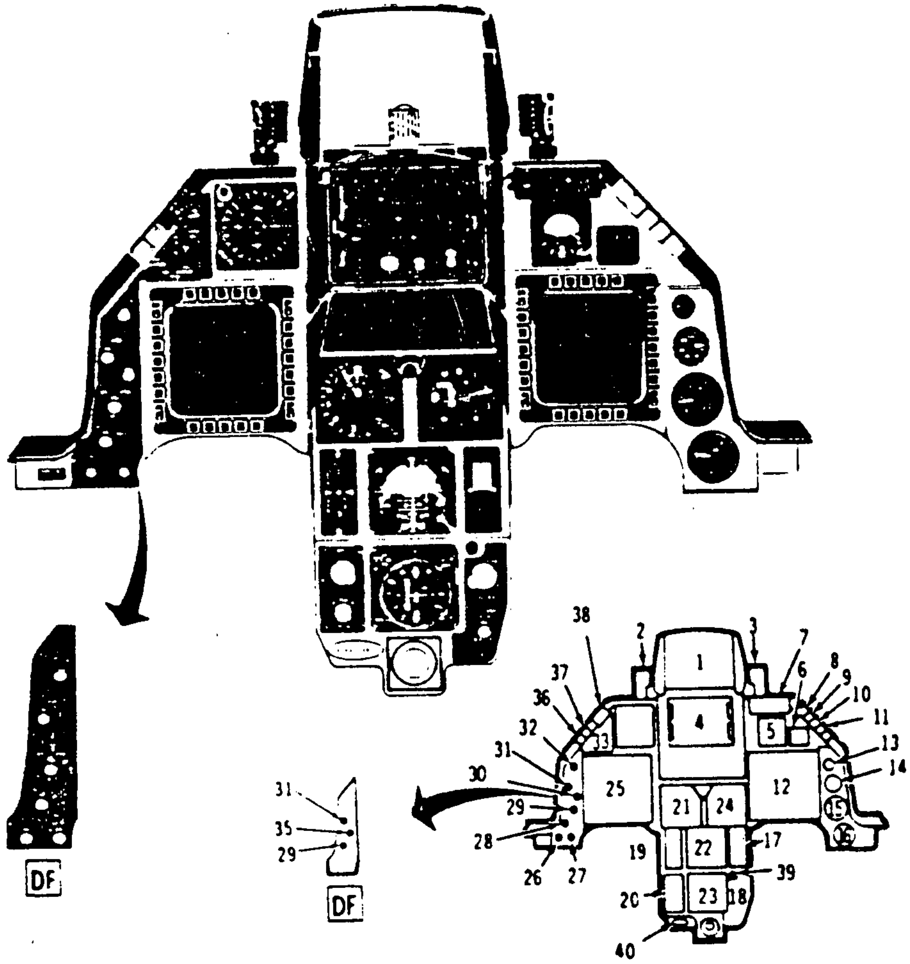


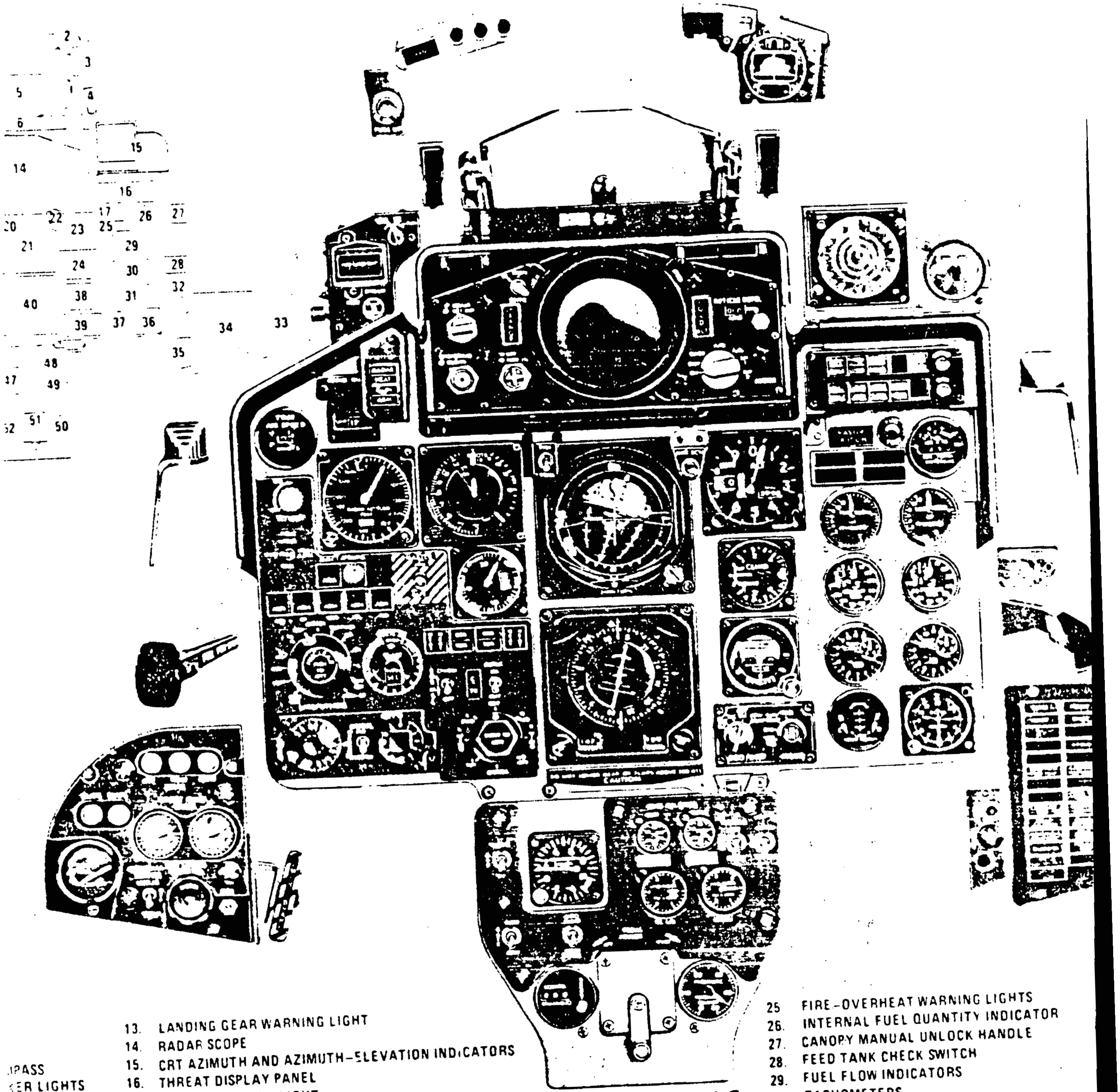
Figure 10B

INSTRUMENT PANEL C DF



1 HUD Combiner Glass
2 AOA Indexer
3 AR Status/NWS Indicator
4 Integrated Control Panel
5 Standby Attitude Indicator
6 Fuel Flow Indicator
7 Data Entry Display
8 ENG FIRE and ENGINE Warning Light (Red)
9 HYD OIL PRESS Warning Light (Red)
10 DUAL FC and CANOPY Warning Light (Red)
11 T O/LAND CONFIG Warning Light (Red)
12 Right MFD
13 Oil Pressure Indicator
14 Nozzle Position Indicator
15 RPM Indicator
16 FTIT Indicator
17 Vertical Velocity Indicator
18 FUEL QTY SEL Panel
19 AOA Indicator
20 Instrument Mode Select Panel
21 Airspeed Mach Indicator
22 Attitude Director Indicator
23 Horizontal Situation Indicator
24 Altimeter
25 Left MFD
26 Autopilot PITCH Switch
27 Autopilot ROLL Switch
28 TF Switch
29 MASTER ARM Switch
30 ALT REL Button
31 LASER ARM Switch
32 IFF IDENT Button
33 THREAT WARNING Controls and Indicators
34 Threat Warning Azimuth Indicator
35 DF OVRD Light
36 TF FAIL and OBS WRN Warning Light (Red)
37 ALT LOW Warning Light (Red)
38 MASTER CAUTION Light (Amber)
39 MRK BCN Light
40 Rudder PEDAL ADJ Knob

Figure 11



FRONT COCKPIT F-4E

IPASS
ER LIGHTS
TISON HANDLE
R
DICATOR
HTS CONTROL

13. LANDING GEAR WARNING LIGHT
14. RADAR SCOPE
15. CRT AZIMUTH AND AZIMUTH-ELEVATION INDICATORS
16. THREAT DISPLAY PANEL
17. MASTER CAUTION LIGHT
18. RADAR ALTIMETER
19. AIRSPEED AND MACH INDICATOR
20. REFERENCE SYSTEM SELECTOR SWITCH
21. ATTITUDE DIRECTOR INDICATOR
22 MARKER BEACON LIGHT
23. ALTIMETER
24. VERTICAL VELOCITY INDICATOR

25 FIRE-OVERHEAT WARNING LIGHTS
26. INTERNAL FUEL QUANTITY INDICATOR
27. CANOPY MANUAL UNLOCK HANDLE
28. FEED TANK CHECK SWITCH
29. FUEL FLOW INDICATORS
30. TACHOMETERS
31. EXHAUST GAS TEMPERATURE INDICATORS
32. ARRESTING HOOK CONTROL HANDLE
33. INSTRUMENT LIGHTS INTENSITY
CIRCUIT BREAKERS
34 RIGHT SUB PANEL
35. KY-28 MODE LIGHT PANEL
36 EIGHT DAY CLOCK

Figure 12

Brig Gen DeHart: I agree with you. The next issue: You have an extremely prestigious group here. If there's any issue that really needs action by the TAF or AF, it ought to come out in your executive summary in the form of recommendations that there was consensus that this is what the AF should do. That report should be sent to HQ TAC for consideration. I think everyone would feel a lot better knowing we'd addressed some of the hard issues and had reached some consensus of what direction we should take. We shouldn't lose that. Shouldn't be some piece of paper that goes into the bottom of the box.

Maj Art Fowler: You threw a statistic up at the start that stated in 59% of the accidents, guys didn't know they were SDO'd. Now if moving the ADI up to that position is going to help significantly, then it's worth discussing. If it's going to help marginally, then the cost is going to override it. I don't like the ADI where it is. I'd love to see it up there, but, only get the feeling that from the statistics, most of the problem results from not looking at the ADI in the first place. I'm not sure we'll get that big a return on the investment of moving it up there.

Unidentified: I see your point but I'm not sure I agree with it. If we had bigger ADIs, I could train pilots to include it in their cross-check where it's available. I think we'd improve the problem.

Unidentified: Let's get a definition of SDO: Some think it's IMC or at night. Others are thinking SDO is flying IMC period. From the pilot's point of view, if that airccraft is on a vector other than what he thinks, he's disoriented. He may know it, he may not know it, but he's SDO'd.

Dr William Richardson: Let's sort out the facts on SDO: We probably can't sort out what happened very easily to those who died unless witnessed by a wingman or he made a call. But if they hit the ground under full power, I think we can assume they were unaware. Milt Miller's training manual talks about maneuvering over rising terrain, unaware it's rising; you may misperceive that your attitude is okay--you may fail to realize the terrain is gradually rising. That's one class of spatial misorientation. Probably combining that with the illusions case where an individual is doing a night aerial refueling and breaks off the tanker into a dead man's spiral, that's a different kind of a situation. If we talk about them as the same thing, we probably are not going to get anywhere. They require different solutions.

Unidentified: Will the ADI influence one solution more than the other? How do you feel about the two separate classes, moving the ADI up?

Unidentified: I feel the rising terrain is purely an altitude problem and an ADI won't help that. You can stare at an ADI all day and it won't keep you from flying into the terrain.

Col McNaughton: We're addressing the rising terrain - CFIT problem with GPWS but I think the Big ADI is important to help keep a pilot oriented in an unobstrusive manner so that he doesn't have to stare at it. You don't want the pilot to stare at anything, for any display, procedure or control that traps his attention can kill him. The idea of the Big, High ADI is to provide him that all-important aircraft attitude awareness subliminally, to his peripheral vision, so he can free up his central focal vision for the crucial tasks of clearing his flight path and maintaining altitude awareness. The Big, High ADI (or Primary Dedicated Attitude Display, PDAD, if you will) is important to help him regain orientation and to keep him aware. In these aircraft with the bubble canopies, the glare and reflections bombard the ambient mode with conflicting, confusing, distracting and disorienting stimuli. The pilot needs a Big, High ADI/PDAD to successfully cope despite all that confusion. What we don't know and what would seem to be an important study is what minimum size of ADI is needed to successfully compete with all that conflict, including false horizons or situations of wrap-around star fields (star and ground lights blending) and no horizon, or with frank vertigo, or with frank oculovestibular disorganization (type III SDO from rapid rolls). All I know is it's gotta be big--bigger than it is now.

Lt Col Gary Matthes: I like to think simplistically. The ADI may handle 90 percent of the 19 SDO mishaps, but it's not going to help any of the other (54 CFIT) mishaps. The SWIM system or Ground Prox systems that AFTI is working on, those will have a good chance to help the 54.

Maj Gary Goebel: That's true because they've got the biggest of all ADIs down low (natural) and that's the one that's outside and they're not looking at it.

Ed Hartman: There are two forums for presenting ideas to improve the problem.

(1) F-16 System Safety Group which includes the EPGs
(2) F-16 Cockpit Review Team

(Unfortunately, the bulk of his comments were not recorded adequately for transcription.)

Maj Harold Gonzales, Hill AFB: I'm Chief of Flying Safety at Hill. The USN and Canadian Forces have gone to HUDs as the primary attitude instrument. I would like to see a statistical comparison between their SDO incidents and ours, the training issues, and also how they certify their HUDs for instruments--to see how we might improve ours for instruments. I'm not sure we can put a big round ball ADI in the F-16A/B where we think we need one, nor from what I've heard in the past few days am I convinced that that's the thing we need. Now if the USN/CF-18 experience is good, maybe we could modify our own HUDs, through software changes, to provide a lot better attitude references using the same visual equipment that we've got right now.

Maj Laurie Hawn, CFB, Cold Lake, Canada: The only HUD I've flown is the CF-13. I came from 5000 hours of flying round dial ADIs and now have 500 hours on the HUD airplane. I fly the T-33 with round dials and the F-18 with HUD, so I'm going back and forth from one to the other, and there's no question in my mind which airplane is more accurate--the F-18; and there's no question which I'd rather be in in all weather situations--it's the F-18. The big advantage is the velocity vector (flight path marker). I'm so comfortable if in any situation where I'm unsure, I put the velocity vector above the horizon and make sure it stays there, and I can sort out anything else. It's just not a big deal. We have not had the accidents, the HUD disorientations. If the mishap was from overloading, it was probably from not looking at the HUD. Like the one we almost had, he was not looking at the HUD; it was not a factor of interpretation. I can't think of any of the Navy accidents that could be attributed to HUD disorientation either. The instantaneous FOVs on both F-18 and CF-18's is 14o.

(Ed. Note: The fact that he can see the horizon indicates he's VMC, in which situation the HUD is great. The problem is in IMC, or in unexpected unusual attitudes.)

Maj Gonzales: With 400 hours in the F-16, I'm wondering why we haven't had more accidents, what with the smallest Attitude Indicator, and the smallest HUD (The smallest FOV). From an operator's point of view, we've got the worst of both worlds, separated by almost 30°. Small wonder why the kid hit the ILS at Hahn.

Dr Richardson: I'd like to ask the gentleman from Hill what percentage of accidents have occurred from impact with the ground when the pilot was flying low level, versus disorientation coming off refueling or going lost wingman.

Maj Gonzales: The only one that comes to mind in high altitude is the kid that did the intercept on the train (in which he lost 11000 feet over a 1-1/2-2 minute period). It required a software change to put a break-X in the radar scope and we haven't lost anyone else from attention-trapping on the radar scope.

Col William Runkle, AFISC/SEL, Norton AFB, CA: There were nine F-16's classified as SDO-type accidents. The remainder were all pretty close to the ground and involved low level situations: Two occurred on radar-trail departures, one of which was totally unrecognized by the individual--a sort of type I SDO. And one of which was recognized but corrective maneuvers at the last second were too late. The only real type II that I know of where the pilot was disoriented and survived was an ANG accident--day departure into IMC.

Col McNaughton: There was the case where lead was referencing an erroneous SAI, not the same case of the erroneous flight plan. There were the two radar trail departures. There was the student at RTU who was coping with a lighting problem plus a warning light, while rolling over onto his back: The ADI was just too small and far out of plane to be sufficiently commanding for him. Another problem brought up by Maj Gonzales is that at night under certain conditions of cockpit lighting, glare and reflections, the entire top half of the ADI can appear to be gray, misleading the pilot into thinking he's level or climbing, when he could be otherwise.

Dr Richardson: Of the accidents we're discussing, could we also divide them not only between those that occurred at higher altitude to represent pilot workload · type of accidents causing disorientation that was recognized by the pilot, but could we also consider the case where he experiences disorientation but doesn't know it and flies into the ground? This is a strong case where we could have the vehicle inform the pilot he's lost orientation, or alternatively, have the vehicle recover automatically. Think about whether there's that difference in types of accidents.

Lt Col Dick Krobusek: Regarding CFIT vs SDO, the one key factor was, which way was up? The cues are hard to read or hard to find--especially if momentarily distracted or disoriented. To discern his real attitude is a real problem. The symbology can probably be changed quickly. You can put anything you want up there. The HUD is still a primary instrument.

Maj Art Fowler: Maj Gonzales said we had the worst of both worlds--a small HUD and a small ADI. Are we trying to advance the HUD to make it the primary instrument, or are we just trying to advance it to help? If we advance it just to help, then we're going to have this pilot's school training problem.

Maj Dick Reynolds: I'm a bomber pilot but I fly gliders. A very useful device in gliders is the audio-variometer--a tone that tells you whether you're climbing or descending. It's very helpful for situation awareness in the vertical. It frees the eyes up for the other aspects of SA. This might help these single-seat fighters.

Bart Brooks: I propose this body recommend improvements to the F-16A/B HUD. Contrary to popular opinion, the Cockpit Review Team (CRT) doesn't have a lot of pull with anybody. The CRT is subordinated.

Ed Hartman, GD: Both the F-16 System Safety Group and CRT need to be involved, whichever has the most influence.

Bart Brooks: I recommend we endorse improving the F-16A/B HUD as an attitude instrument and change 51-37 to reflect that.

Col Gary Matthes, Edwards AFB: I'll make sure the operators and combined test force is made aware of that. If they say to change it, we can.

Maj Art Fowler: If we improve the HUD and make it a primary instrument, it's going to give IFC a job determining how to train it.

Lt Col Bill Ercoline, USAF IFC: AFM 51-37 is a users' manual. If the user wants to use the HUD as a primary instrument, it'll be written that way; in fact, we're writing a chapter to use in instrument conditions right now, but we can't get a consensus to say that's how we should do business, strictly on the HUD. And I caution you to say that. What I've gathered here today, what I've learned over the past two years since IFC's been back in business, I'm not sure you can say that right now with all the HUDs we've got going in the Air Force at present. We have another system now that works--we know it works. If you want to include the HUD in there, we will, but to call it the primary flight instrument with all the variations we have, there's no way you'll be able to write any procedures that are standard. Until we can get a better handle on that, you can't write it.

Training: For two years we've been trying to get some type of advanced instrument training program going where we can educate the IPs, to get 'em back into the system to teach pilots on how to develop a better cross-check than this "T cross-check." The old "T cross-check" is gone anymore, so they'll have to do something. In the T-38 maybe we should start teaching use of the SAI--it's ideas like these we ought to plough back into the system. A lot of our IPs have no idea what the cockpits of modern fighters look like. It's a weakness of our system, so training is a weakness. But 51-37 is your manual and we'll put in whatever you want. What's coming is an annex on how to fly HUDs.

Maj Dick Reynolds: I'm not ready to say teach HUDs in ATC. I'd rather see them well versed in basic instruments. If he's well trained in basic instruments, I can teach him the HUD, but if all he knows is the HUD, it'll be very difficult to get him back to basic instruments--and he may go to an aircraft lacking a HUD like a C-141.

Unidentified: I beg to differ. I think we should teach HUDs in UPT. That flight path marker is so valuable. At least some sorties should use the HUD.

Col McNaughton: Let me run by you a couple ideas on improving the HUD as an alert to unusual attitudes. Note I said alert--not to function as an attitude instrument by itself. I hope we've made the point that by the HUD you can't tell, at a snap glance, upright from inverted, or climb vs dive, or to about what degree. Also, the dynamics of the HUD are such that you can't read the numbers on the flight path scale during rapid rolls or pitching maneuvers. To tell where you are, you must first slow or stop the roll or pitch. Allow me to take a moment to introduce a couple ideas to improve the HUD as an attitude alert.

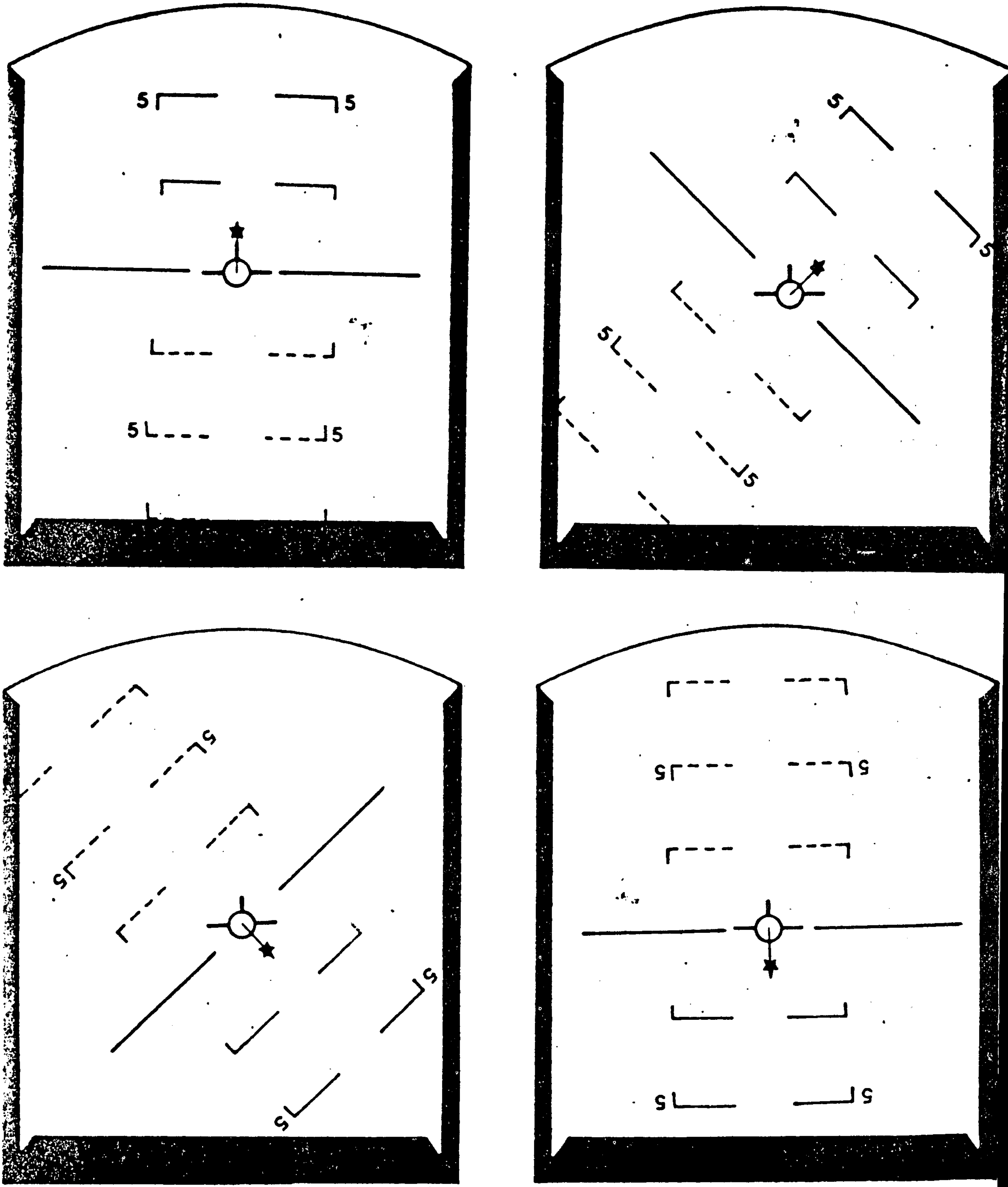


Figure 13: Depiction of HUD's Showing Vertex Pointer on FPM with various attitudes.

First, the HUD provides lousy roll cues since roll angle requires interpolation between the tail of the FPM and an imaginary line extending from the center of the FPB toward the vertex running between the Flight Path Scales (FPS). Also, the quickest route to upright is not always apparent. Though the horizon pointing tails on the FPS's may help you find the horizon, they don't necessarily help get you upright. Despite the fact the FPM does not roll relative to your aircraft (being an inside-out display), it is the most commanding symbol on the HUD. So to improve it for attitude alert in roll, why not add a vertex pointer to it? (Fig 13). A line coming out of the FPM with a star (for sky) might serve well--would provide a distinct pattern for various roll angles, especially upright vs inverted, and would tell the pilot which way to roll to get upright quickest (simply roll the tail of your FPM towards the vertex pointer). The star is Dick Malcolm's suggestion and may be better than using an arrowhead, because it's more intuitive. Dick Newman is going to test this.

Second, to provide a better alert to pitch attitude, radically change the pattern of the FPS from climbs to dives, and since the dive is the more critical, again radically change the pattern within degrees of dive, say every 30 degrees (Figs 14 and 15). Again, the idea is not to make the HUD a primary attitude instrument, but to make it an attitude alerting display which tells the pilot to go to the ADI--which really is the primary attitude display. (Note the pitch scales become increasingly commanding the steeper the dive, resembling "Jaws".)

Paul Metz, Northrop: The idea's good, just be careful of cluttering.

Maj Art Fowler: At rapid pitch/roll rates, small pattern differences won't register--keep 'em bigger and also consider angling the FPS (especially those negative) like chevrons, increasing the angle with increasing dive angle.

Unidentified: I've noticed that during loops, going through the vertex or nadir produces a controlled precession of the FPS that I find very disorienting.

Unidentified: Vertical maneuvers are best done on the ADI, especially VFR, then it's easy to stay oriented.

Col McNaughton: Don't forget the inverted dive situation. Col Kehoe's incident occurred on a CAVU day, and as he said, when you're 60°-70° nose low, inverted, you can't find the horizon; it just doesn't register. I've been there doing inverted spins over dry lake bed. You can't find the horizon and you just don't know where you are.

Unidentified: To prevent that, need train cross-checking the ADI.

HUD PITCH SCALE SHOWING
RADICAL CHANGES FROM POSITIVE
TO NEGATIVE & WITHIN NEGATIVE

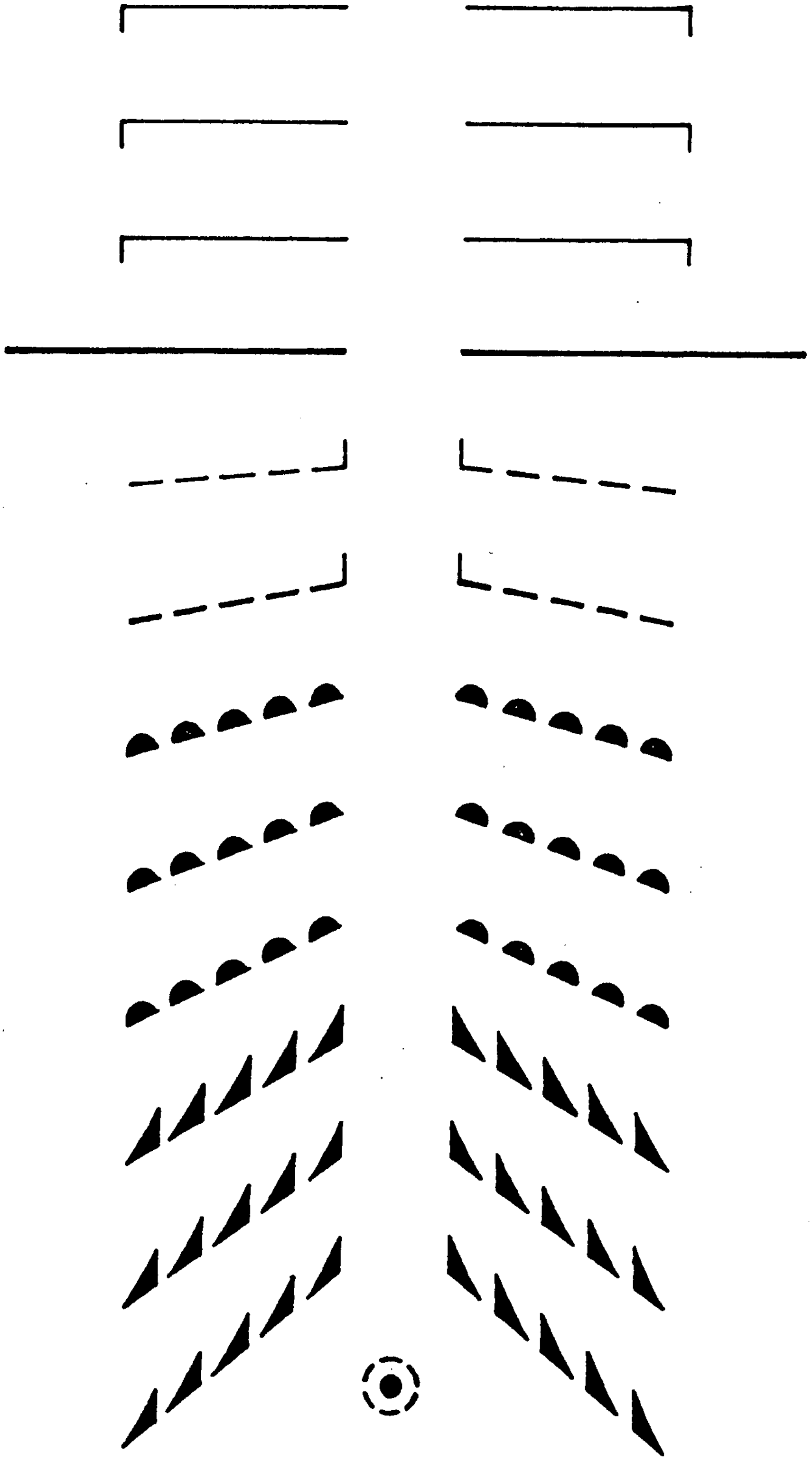


Figure 14

COMBINATION OF VERTEX POINTER ON FPM PLUS RADICAL CHANGE IN FLIGHT PATH SCALES FROM POSITIVE TO NEGATIVE

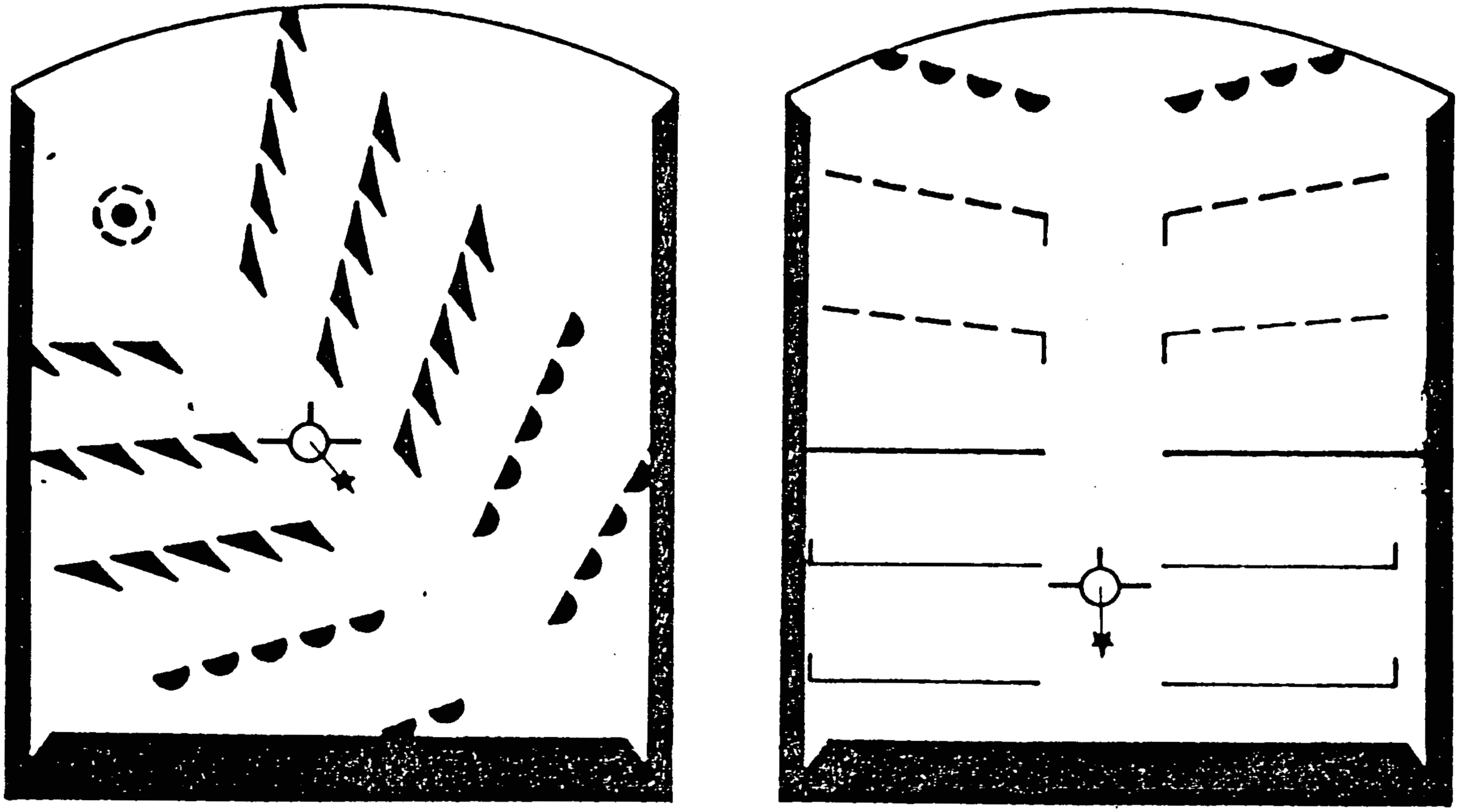


Figure 15

Col McNaughton: In the heat of battle, guys are going to do just exactly what Col Kehoe did. They're not going to stop and check the horizon. They're going to think they're really upright when they aren't. There are all kinds of things out there that make guys think they're upright when they're not; like canted cloud decks, false horizons that cue your subconscious so you don't even think about it. You automatically assume you're wings level when you're aligned to something else, like your wingman or bogey. You can train, train, train--but it's almost impossible to train out ingrained innate responses.

Unidentified: What do you have to get him out?

Unidentified: Maybe a big ADI will help the 19 accidents (due to SDO) but Kehoe fell in the other larger (54) group. He got to concentrating on a task. It's distraction from the task of flying.

Unidentified: What happens to Col Kehoe if he's flying an F-18, he's got no ADI, he got dark blue sea and dark blue sky and he can't see the horizon? He's going to have to pull according to the SAI or HUD, and if it starts precessing when he gets near the bottom, he'll be in trouble. Note the first thing Kehoe does when he realizes he's in trouble is go to the ADI - white over black.

Unidentified: Could we color code the HUD and would that help?

Unidentified: Possibly in the future, but no way can we provide the degree of contrast difference of an ADI onto the HUD without cluttering excessively.

Unidentified: For fighter pilots, keep it as simple as possible--and that's what the ADI does.

Unidentified: Amen!

Don Gwynne, GD: Reviewing F-16 CFIT mishaps, I count 12, amounting to 23 percent of USAF F-16 mishaps. Of those 12, I personally investigated 5. If we accept type I SDO as misoriented, i.e., he's not well oriented but he's not afraid, is that the proper definition? Of these 12 CFIT mishaps, only 2 didn't fit this pattern of misorientation without being cognizant of it. One of them I believe was consciously disoriented and afraid. The other knew full well how he got where he was, and how to get out, but just didn't have the room. Of these, I asked how many were looking at the HUD. In 8 of 12, the pilot almost certainly was not looking through the HUD, or at the ADI. Of those remaining, you've got at least one where probably he was looking through the HUD, two where maybe he was looking through the HUD. Bumping into the ground when you're not afraid is really the leader here. All of these point to some sort of Ground Proximity Warning as the place to invest your money, rather than updating displays.

Col McNaughton: The argument with this position is that the GPWS doesn't help keep you oriented whereas a well-designed visual display would help keep you oriented, ease the job of operational flying, and thus tend to free up time to maintain terrain clearance; i.e., a good attitude display might reduce the need for a GPWS while improving effectiveness.

Don Gwynne: If people have trouble imagining how you can fly controlled into terrain, let me remind them of:

- Descending slowly into ground while focused on radar scope (at night).
- Running into the side of a mountain while typing the FCNP.
- Slowly descending into the Great Salt Lake while you think your auto-pilot's keeping you level, while looking for your buddies on the TACAN Radar.
- Looking at a train at night mistaking it for your target.

The great majority of these would not be affected by either the HUD or the ADI.

Col McNaughton: What do you think of Dick Reynold's idea of a variometer, like on a glider? What do these cost?

Lt Col Don Ross: We're not flying gliders.

Lt Col Dick Reynolds: We need an audio warning of some sort, not continuous, but perhaps a ground proximity beep in the ear sort of thing, till he responds.

Col Bill Runkle: I'd like to clarify something: Spatial disorientation and controlled flight into terrain. I feel that 7 of the 9 F-16 mishaps were CFIT because they didn't know they were disoriented and there's no evidence any of those seven were looking at any sort of instruments. In many instances, something else was going on in the cockpit--a warning light, looking at a checklist, radar to the proper range, or other distractions. Had they been looking at their instruments, a lot of those guys might be here right now.

What we're talking about here is that the F-16 aircraft has some characteristics that make it particularly tricky when you're distracted, low level, or in the weather. It's smooth and you can get into a sub-threshold roll or pitch change without being aware of it. The instrument flying equipment provided in the F-16 is rather small, and it does not command a lot of visual response, especially from the ambient part of your vision, if you are distracted. What we're lobbying for is something more prominent, something a guy could catch out the corner of his eye if he were distracted, and something to help him like a ground proximity warning system. Now the GPWS, I think, is great. It may be the only thing you can do. You cannot move hardware around in the limited space and provide the guy a two-foot ADI. Since you can't fix the ADI, why not improve the HUD to make it better suited an easier for instrument flying?

Unidentified: ADI by itself won't fix the problem.

Unidentified: We do not have a GPWS now nor do we have a fly up.

Ed Hartman, GD: We have a number of things being considered for the F-16: A line-in-the-sky barometric altimeter, probably ready to go close to a year ago. We recognized a visual only system was insufficient, and we'd want an aural warning system as well, either via a tone or via the voice message unit. We recognized that was insufficient and stated they needed an aural warning system to say, "Warning, Warning." The multinational cockpit review team said we don't want "warning, warning"; we want a tone. Well, what kind of tone? We went back and forth. What were the words used for: Everything. We also had a capability for a Voice Message Unit that would say, "Altitude Altitude," or "Pull up." Political issues--I don't like this or that and that's it. So we've got a line-in-the-sky barometrically based warning system that's visual and aural. The CARA (Combined Altimeter-Radar Altimeter) system coming on. Also have the ground clobber system (a visual system only that provides flashing X in a HUD using an algorithm based on gross weight, TAS, AOA, VVI and radar range to compute a ground impact point; the flashing X commands a 4 G pull within 2 seconds to miss the ground) in all air-to-ground modes, not air-to-air. We have a study proposal to get air-ground range information and put in air-to-air modes to give you a pull up command so it's a no delay, immediate response system. We'll bring in radar altimeter with the other sensors to provide a predictive GPWS. We're going to get a widespread GPWS for the F-16A/B. For the C/D we'll integrate these into the ground clobber mode. We've a lot of proposals in and it's a matter of getting the budget approved. We'll get the VMU. With the coming of ECT 1085, the three altitude/ground collision warning systems (line-in-the-sky, CARA, and ground clobber) will be integrated and operable in all modes (air-air, air-ground, and navigation) in the Block 15 F-16A/B aircraft. There's a plan to eventually integrate this into all Block 10 F-16's too.

Maj Art Fowler: We already said we don't see anything if we're not looking there for it. I need something better and I need it now.

Ed Hartman: We need inputs from the USAF to know what you want--training--red light, yellow light or flashing light.

Unidentified: Block 15S will have much of this. We can't do it all at once.

Bo Gehring: Voice can be very effective if used properly. What would you want it to say?

Ed Hartman: Warning, warning; Altitude, Altitude; Pull Up, Pull Up...

Unidentified: "Too late, too late"--laughter.

Lt Col Mike Lichty, TAC/SE: I'd like to go back to what Don Gwynne said: We're not looking at the ADI or HUD when we fly into the ground--so one is a training issue--we must train to do the right thing at the right time; the other thing is we've got an airplane design with a pilot-aircraft interface in which we're gonna be subjected to SDO in the F-16. So now we have two tasks at hand.

(1) To provide him a cue to return him to attitude awareness or to an attitude instrument.

(2) The other task is to evaluate the cockpit he's flying to determine whether his attitude information is readily available and easily interpreted so that he can recover.

We have a law that says he's gotta pull 4 G's in 2 seconds; if it takes 6 seconds to locate, read and decode the attitude display, I'm dead anyway.

Lt Col Dick Reynolds: Get the guy's attention to the attitude indicator's information. Put it up so he can find it easily and train him so he knows he's got to use it. To reiterate:

(1) Do something to tell him he's in trouble and he's got to use whatever's available to reestablish what his attitude is-- to regain attitude awareness.

(2) Clean up the HUD or the vertical situation display (VSD), or do whatever you can to relocate the ADI within capability so that he has got useable information. And I think some of your suggestions regarding improving the HUD as an attitude alert are great. Might as well standardize 'em while you're cleaning the HUD up.

(3) To reiterate Bill Ercoline's plea: Standardize USAF training by whatever documentation is available; and through MAJCOM training shops, you educate the pilot population to the problems and how they can fight it.

Lt Col Lorenzo Pugh, HQ USAFE/SE: We need to make some recommendations that we can implement right now. The other point is that we're getting a lot of anecdotal reports, near misses, close calls and talk at the bar, that's getting to form some of those things we're studying. I've had SDO several times and scared the shit out of myself and I'm sure the other guys have also, and I think we're hearing some of that in the bad-mouthing of the instruments. But that doesn't show up in the statistics. There are only nine mishaps, but there are probably 900 almosts. All that means is that the problem is there and it's real, so we'd like to do something about it.

David Pannkuk, Perceptual Dynamics Research, Milford, OH: I'm David Pannkuk and I have zero hours of flying (laughter). I don't think you can teach a monkey to fly; perhaps a gorilla (laughter). All I know about flying is I don't like it. It bothers the hell out of me. We've talked about training and we've talked about vision. We haven't talked about training vision. You've been told there are limitations to what we can do. You've been told we have a focal system that's truly keen, that the focal vision is conscious, and the ambient system is subconscious. The problem is that we're not working with trained levels of vision. If you were to measure perceptual activity as a skill in any performance you want to prescribe, it would come out as spastic, disjointed and disjunctive. Flying is a perceptual, working activity. It's hard work, primarily because you're overloaded with stuff you cannot see. In WW II, early on, it was a fact that of every 3 planes shot down by American servicemen, one was a friend. Now their skill in gunnery was uncanny--but their problem was distinguishing friend from foe. As an 18 year old kid on board ship, I can tell you we didn't give a damn who he was--he was flying and I was shooting. How long did it take the USN and the AAC to realize that the red ball in the center of the American star was identical to the red Japanese ball? How long did it take for them to get that out of there and put a bar across so you could identify? In the British raid on Dieppe, 91 planes were lost; 62 were shot down by British guns. USN pilots were scared to fly past a destroyer after an action, for damn good reason. On Kodiak Island, they were using 55mm shells to shoot any plane down that came over. There was a warning out for Kodiak--don't fly over Kodiak.

The United States Navy (USN) was confronted with a training program they called WEFT (wings, engine, fuselage, tail) for aircraft identification.

The USN went to Dr Samuel Renshaw at Ohio State who'd been doing some basic research on how to train people to see. This has always been a problem. It goes way back to the early days of World War II, to train pilots to know how to see. The training was instituted; there was a complete reverse. The kill ratio was 99 enemies to only one friendly. What you've got to know is my perspective on things. What you've got now is a situation where you've made an aircraft highly capable of climbing rapidly to intercept like a pergrine falcon, and you've insured that the major component in that system is a pilot with the visual attributes of a myopic penquin.

Not that they don't have the capacity. Let me ask you a very simple question. You're looking at that display. Which would you prefer to do when you're recognizing words? Have a visual skill that would take you approximately 1 second to cover or visual skills that would take you 1/10th of a second? Which is going to make you more comfortable with the information coming into your eye? You've got a hell of a lot of confusion. You've got a tacky visual display. What do you do when you hit break distance at 3000 feet and you've got 1.2 seconds to make up your mind? What are you going to do with the visual skill, a level of vision, that works at .25 seconds to 4 or 5 characters per look. You can speed yourself up against the wall. You can put in training tasks till you're blue in the face. You've done training backwards, forwards, upwards and down, but you haven't done enough. If you put in training for task performance, you will have overloaded the basic underlying skill to make that happen. You'll be no better off tomorrow than you are today. Is that where you want to be? You haven't got any parameter described except attitude. I'm not even sure you have a good vision check as far as quality, but nowhere do I see anything in the Air Force or in the Armed Services that tells me that you know how people work with their vision. Do studies. Find out what the difference is between somebody that can handle the situation and somebody that seems to grind himself into the ground. And I apologize for being so long.

Col McNaughton: I'd like to say one thing in defense of the way we do select. We are doing some work looking at the contrast sensitivity function. I might add that one of the services that's known well for their skills in pilot selection is the Israelis. They don't do anything special about vision selection. They have the same thing we do; they just use Snellen charts and require, I think, 20/20 or perhaps 20/17. What they do is select candidates on their ability to switch their attention quickly, and they do a very simple test which we have not yet instituted in our Air Force. But we're evaluating it at USAFSAM now. It's called the Dichotic Listening Test, which is the ability to switch your attention quickly without losing track. Some of these things probably need to be looked at. Unfortunately, we haven't broken the code on a lot of this yet.

Mr Pannkuk: We can give you an assessment of how it would work. We can give you a technology that will allow that to be taken in. But we say, well things are like this. Then we establish norms, great norms. The person who performs visually versus the nonperformer is the difference between night and day; there's no comparison. We're talking about a virtuoso versus a beginner.

Unidentified: I have a question. I don't understand what you're talking about. Are you saying we ought to be screening pilots?

Mr Pannkuk: No! Training pilots.

Unidentified: All right, could you expand a little more for my benefit? I don't quite understand. We're obviously going to train through areas where previous groups of students have been. Now I need to know what that is.

Mr Pannkuk: All right, there's a standard required for flight. Find it out; make an assessment of what capabilities you want available and determine them. If you find out, we'll help you on that. You find out what it is you're going to provide to allow that to happen. We describe to you where the variables can be put. But you set the parameters. What is it that you want? You tell me what you want in terms of response time from a person looking at a HUD, ADI, Head down, Head up, I don't care which.

Unidentified: Are you talking about the kind of training they did in WW II where the guys used silhouettes?

Mr Pannkuk: That was the basis. The key here was the flashing of silhouettes followed with training.

Unidentified: Expansion of vision was one idea, another was speed reading, teaching the pilot what to look for on the HUD, when to look at it and how often.

Mr Pannkuk: We can train vision and we can train attention.

General discussion followed that was inadequately recorded for transcription.

Dr McNaughton: Can we build the displays better so he can get the information he needs at a snap glance out the corner of his eye?

Maj Harold Gonzales: If we could publish today a syllabus on training that would increase my perception several times, I think we ought to recommend that somebody look at it because I haven't gotten training one in the Air Force in 14 years that has increased my perception of anything. If this exists, I think we ought to take a look at it. For example, going over intelligence photos of airplanes fairly often should improve your ability to detect things, but only once every six months is probably not enough.

Maj Steve Detro, Ohio ANG: Maj Milt Miller's low altitude awareness program does that. It teaches you what to look for on the horizon at 100 feet, what to look for out the side window, how to get that speed rush and what to do about it, mentally and visually, and you're gonna see more of it and hear more about it. It's in physiological training now and also shown on VTR.

Question: Does it improve your ability to take in more at a snap glance, in a very short period of time?

Maj Steve Detro: Yes, because it trains you to look selectively to see the velocity vector in relation to the pitch line. And you can tell just by that much whether you're going to hit the ground in the next 3 seconds. It trains you to get what's important in minimal time. It's a very good program.

Lt Col Gary Matthes: I know this sort of stops this discussion, but I'm afraid there are some things we're not going to get in the executive summary. What we said before is good, and that takes care of getting things done in a hurry, but something has bothered me for the last 13 years of flight testing. I've seen many airplanes come into the inventory and with different airplanes, we go about things differently. In cargo aircraft, one of the biggest requirements in its Request for Proposal (RFP), and because of the way they flight test, is instrument qualification of the system. I talked to Major Rounds to see if he runs his tests the same way and he wasn't sure, but I bet they have some way to check the instrumentation. I bet if you look at the F-16 RFP, you won't find a damn thing. I'll bet you won't find a thing in the Advanced Tactical Fighter RFP that was just let. We don't even concern ourselves with it, and one recommendation ought to be that when ASD lets out an RFP for a new fighter, they ought to force people to at least think about it. These considerations should be part of an RFP. In addition to be able to turn 9 G's at 50,000 feet and go 1.2 on the deck, by the way, he has to have a Ground Proximity Warning System, and it has to have some type of attitude warning system. You have to have attitude systems that allow it to be flown easily in IMC. Fighter pilots just don't worry about that and they forget. Although you may go out and shoot a bogey once a month and you may go air-to-ground once a week, you come back and land everyday. And if you're in Europe, you come back and bust the ceiling everyday, and we don't address those. I'd like to see this group put forward that we need to address the way we ask for things in fighter work, in our RFPs or in whatever form it takes to request the things we need in fighters to optimize them for the night-weather role. The bomber and Navy guys should make sure it's part of their RFPs too.

Dr Robert Taylor: Design-wise, you don't want to make it (the HUD) cause a problem: you want to have something down below (like a big ADI). Regarding training, I can train ambient/peripheral vision. By masking out the center, I cause my subjects to make use of their peripheral vision.

Lt Col Dick Reynolds: In order to provide a realistic rerspective to justify our recommendations in terms of cost, not just in lives, but also in taxpayer dollars, we should be able to assign a dollar cost to these categories of mishaps.

Dr Emily Howard: The impression I'm getting from the discussion on training and designing better displays is that all of you are suggesting issues that are true, but what we need is a model that lays out exactly what is true about a pilot's perception in the cockpit. I mean there are certain immutable hard-wired facts about the visual system that cannot be changed by physiological or any type of training. Areas we might improve with training include attention--to switch attention, to train attention to peripheral stimulation, and also the interpretation of information; by just exposing hours and hours to the ADI, we can improve the facility for interpretation till it becomes second nature to 'em. Talking about training, we should look at both of those issues. One the issue of attention, switching attention, being able to select information appropriately and also to interpret information as it's offered, so interpretation of it becomes second nature. But on the other side, we have these hard-wired features of visual perception that should be considered in the design process.

Dr William Richardson, Northrop: I'm going to engage in a Socratic Dialogue with the audience and ask a few questions.

Do you think that any person can be trained to be a fighter pilot? I think that you will agree there are unusual characteristics that we are looking for that will make an individual more suitable as a fighter pilot; we can hypothesize that there are a whole range of behavior characteristics that we are looking for. We want somebody who has good vision, maybe different kinds of vision, maybe just one kind of vision. Ability to divide your attention. Certainly good health and reasonable intelligence; stubbornness; maybe a little macho willingness to extend yourself a little bit beyond your own capabilities. All of these things we fit into what we call our selection criteria for pilots, and I submit that the selection criteria we're using right now overlooks some significant physiological and probably psychological variables that we should be looking for. That maybe in the population of people that we are selecting are some individuals who are predisposed to this G-induced loss of consciousness, and possibly also to this problem of disorientation. Now the evidence that I submit is the study that was done by Sem Jacobsen of Norway, and his colleagues in the 1950's, If you remember, those of you who may recall the study, he looked at a group of NATO pilots. If I recall, there were 55 pilots. He took those individuals and put them one by one in the back seat of a T-33. He took them up and put 6 G's on the airplane. He found they all lost consciousness. What was interesting was when they recovered, about 15% of the individuals showed evidence of something like an epileptic seizure. They became quite unable to control the vehicle; they were disoriented for seconds up to minutes after they recovered. He didn't know what caused this. He hypothesized that when the blood drains from the brain, and then upon release of the G, the blood comes back up and hits the vascular bed in the brain, it causes a shock effect similar to what inches an epileptic seizure in individuals who are predisposed. Normal people don't behave that way. But in that population of people that we are selecting for pilot training, there may be individuals who have this characteristic who don't know it, who are not tested for it, who may never encounter it until they go up by themselves in a single seat fighter and put a lot of G on the airplane, and suddenly find themselves dead. End of discussion.

Unidentified: What was the question? The question was, "Can you train everybody to be a fighter pilot?"

Brig Gen DeHart: We are now aiming for an October 1986 date to begin fighter-specific physiologic training at Holloman AFB for Lead-in Fighter Training (LIFT). They'll have 2 to 2 1/2 days of ground school with special emphasis on SDO and GLC, followed by practical experience in the centrifuge and a spatial training device like the vertifuge. They'll be monitored to ensure they learn what is necessary.

My next point is pre-screening. If their G-tolerance is low, we'll train 'em. We'll not ground them medically under any circumstances. But once we get this program going at Holloman, if we find someone on the low side of the bell shaped curve regarding G-tolerance, we'll shuttle him to the Tanker-Trainer-Bomber track.

Mr Dick Newman: You know, one thing that drew my attention here is that a lot of the psychological studies of orientation and disorientation are done with the average college sophomores, not pilots. One thing we've already done is screen for all kinds of psychological tests; one I remember is a large segment of tests dealing with the ability to orient. Pilots, however, are not the standard population a lot of these psychological tests perform research on. You have to be careful in applying these conclusions to the pilot population.

Brig Gen DeHart: It's very unusual to find a pilot that can't be trained to pull G's.

Maj Laurie Hahn, CFB, Cold Lake: That selection process here of taking a guy off the street and putting him in a centriifuge and whizzing him up to 9 G and see if he can take it, obviously it's not that simple, but that scares the hell out of me. When you get some guy who really wants to join the Air Force, really wants to fly fighters, comes in, you're going to stick him in the centrifuge and whiz him around at some specified G, and if he can't hack it, forget it. You're going to lose an awful lot of guys you shouldn't be losing.

Brig Gen DeHart: I'm talking about UPT graduates--they're already pilots now.

Maj Laurie Hahn: Our medical people wanted to do something similar to that. We said, "Just a minute". Well, I say the guy comes in off the street and he wants real bad to join the Air Force and fly fighters and he's scared of failing, and you put him into a centrifuge, whiz him around at 9 G and he goes unconscious and you say, sorry pal, you're out of here.

Dr William Richardson: Wait. I'd like to make myself clear on this. What percent of the accidents that we've discussed here have been due to the fact that there may be physiological limitations in the individual who died that we didn't know anything about? If you try to treat a situation as though it were simply a hardware problem or a software problem, you're missing the message. The problem is it's very complex, and it could be partly the individual who was behind in performance.

Lt Col Mike Livingston: G-tolerance varies from day to day and moment to moment--could vary from 5-9 G--that's why training is important.

Col Gary Matthes: Inability to train a candidate to pull the G's may also reflect undermotivation.

Dr Richardson: Those people who are physiologically inadequate in terms of being able to tolerate G may often self-select themselves out of the program, or it may show up in the accident statistics, and what we are talking about here is some percentage of these accidents possibly could be traced to that position. Though there may be defects in Sem Jacobsen's study, there was no evidence that his study was wrong.

Dr Kent Gillingham: I've seen more cases of G-induced loss of consciousness than probably anybody here. I've been working with the centrifuge for approximately 8 years now. There is a bell shaped curve. There are some people who've had the exposure who cannot do it. They have G-tolerances that are at the bottom 5 percent, the bottom 1 percent. I think it's idiotic to try to select that type of person to fly your 20 million dollar aircraft. Where do you want to draw that cutoff line? Do you want to draw it at 50 percent of G-tolerance or 95 percent? That's up to the Air Force. There are people who are physiologically deficient; they just can't tolerate G's as well as other people and it seems there are other options for people like this. We're talking about people who can tolerate 9 G's for 45 seconds consistently; I'm not talking about day to day variation. On the other hand, there are people who cannot tolerate 4 G's for any length of time at all. There are a number of factors that relate to G-tolerance and all add up. But there are certain biological capabilities that you start out with. Take an individual and give him weight training and frequent exposure to G's. Give him a good straining maneuver and the proper equipment. He'll have a super-G-tolerance. Take another guy and give him the same things, and he's not going to be a super-G puller. I think that we have to make sure we start out with the best protoplasm that you can get and go from there. There's no sense taking a deficient condition right at the very beginning, and I'm not talking about anything extreme here. I think that almost everybody that has completed undergraduate pilot training is okay. I take that back. Most of the people you know probably would have made the 8 G's in 15 seconds' tolerance standard: a reasonable standard that almost everybody passes. I think it would be inappropriate to take someone who you know is going to give you problems, especially when we're operating on the ragged edge of human capability under some circumstances in high performance type of aircraft. For them, the situation is going to get worse, not better. Their selection is going to harbor some real potential mishaps in the future Air Force.

Dr Sheldon Ebenholtz, Univ of Wisconsin: There's an aspect of ocular motion that may relate to acceleration. There are a number of responses like smooth pursuit, vergence systems, etc. It seems to me these should be considered in pilot selection. Several of these systems are adaptive: For example, the vestibulo-ocular-response, which compensates for rapid head movements, enabling your eye to stay on target. These are highly adaptive systems. It may be that pilots who exhibit compensation are better adapters. We know that one segment of our college population will not adapt and another percent will. There are people whose systems will not adapt. There are others whose systems are highly adaptive, then there's a group in between. It strikes me that intelligent screening might be able to sort these out.

Unidentified: Do we know whether we want those who are highly adaptive or nonadaptive?

Dr Richard Malcolm: We don't know. There are great variabilities in human performance. One student in UPT was having trouble judging his turns. One day driving his sports car, he attempted a left turn, misjudged it by 25 feet and went through a chain link fence. He was stone cold sober. In order to estimate the curve of that road to plan the trajectory of that curve is an integrative function. He admitted he was never able to learn to do that. When you think about how high a level of computational activity that takes, or doing actions like throwing a ball and making sure it's going to get there, those require a high order of integration. It's during UPT that instructors need to recognize and filter out the guys that can't hack it. It's very subtle, highly dynamic, requires good judgment and a lot of savvy. We need to be prepared to do that--to understand it so we can properly train the instructors and fine tune their skills at recognizing innate deficiencies in their students.

Brig Gen DeHart: Selecting the right people becomes even more critical in combat, where a weak individual can let his entire element down.

Marty Martinez: I flew the F-84 and my experience was working with the ADI. Seems to me we could use something additional to get the guy's attention and alert to unusual attitudes. I'd like the ADI moved up right below the HUD.

Unidentified: One of the problems we have is that the HUD is a fighting instrument, and looking through it, pilots hate to see anything flashing or moving. We don't want the clutter, either. The HUD's a distraction while fighting though it helps while flying, and we spend much of our time fighting. We commonly punch de-clutter.

Col McNaughton: I'd like to ask Jerry Gard if you could put a texture change on the HUD to represent the surface, to increase sky-surface contrast?

Dr Jerry Gard: You can do anything you want, but pilots won't stand for all the clutter.

Maj Art Fowler: They declutter all that stuff now, including the FPM and pitch scales.

Mr Paul Metz: Somebody tell me what percentage of the 73 accidents flew into the ground due to lack of cues versus flying into the ground due to fixation, or due to spatial disorientation or GLC.

Brig Gen DeHart: SDO is number one in the TAF; it leads GLC.

Col McNaughton: The F-16 is running over 2:1; SDO/SMO mishaps are at 9-12 depending on how you look at it. GLC is at 4, so ratio-wise, it's 2 or 3 to one, SDO vs GLC.

Mr Paul Metz: We've got so many reasons for hitting the ground, how do we know what's the most important - SDO vs the high speed low level (HSLL) collision with ground mishap?

Col McNaughton: Percentage-wise, in the F-16, SDO's the bigger problem compared to GLC. GLC's a big problem but not as big as the SDO problem. SDO constitutes a segment of the overall distraction, misorientation-disorientation problem producing collisions with the ground. We've had 12 SDO mishaps and 19 CWG. To my way of thinking, both are part of the overall loss of aircraft attitude awareness problem. The attentional problem is basically a ground-proximity warning problem: My idea is that if we provide displays and cues that can free the focal mode up to attend to the flight path and cue him when to look ahead, perhaps we could solve most of the CWG and misorientation problems.

Maj Art Fowler: I'd like to see something come out of this meeting that deals with current design deficiencies. We ought to specify that all future aircraft will have certain things: they will have a radar altimeter; they will have panelescent lights; we will have an internal lighting system that's commensurate with the night air-to-ground role; all will have a GPWS. There are 4-5 things we know damn well we need and we keep missing them, then the retrofit mod costs a lot of money. We should incorporate those things up front and save time, lives and money. That's the only way we'll get them because otherwise they'll design around them. Put the equipment in a simulator and test it, then into a combat aircraft and fly it, and put it in production aircraft.

Unidentified: There's the danger of extending the basic acquisition process by ten years. Basic research is very important, here, but it takes funding.

Col McNaughton: May I just throw out some ideas for improving the displays? How about moving airspeed and altimeter tapes that look like these (Figs 16 and 17), incorporating a distinct change in pattern from one range of airspeed/altitude to the next?

Dr William Richardson: I think they're excellent ideas and would like to see them tried in the simulator.

Col McNaughton: Major Fowler mentioned the night-role needs. Does that vugraph include most of them?

- o To improve attitude references, to include a large Primary Dedicated Attitude Display (PDAD).

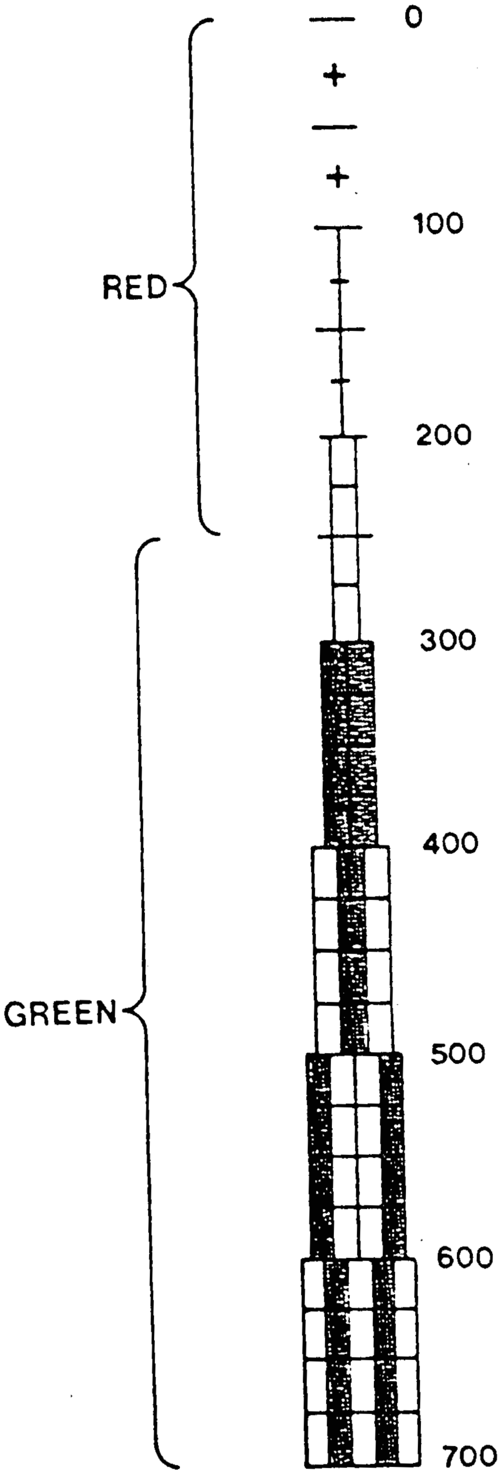


FIG. 9 - SUGGESTED MOVING TAPE FORMAT FOR AIRSPEED INDICATOR

Figure 16

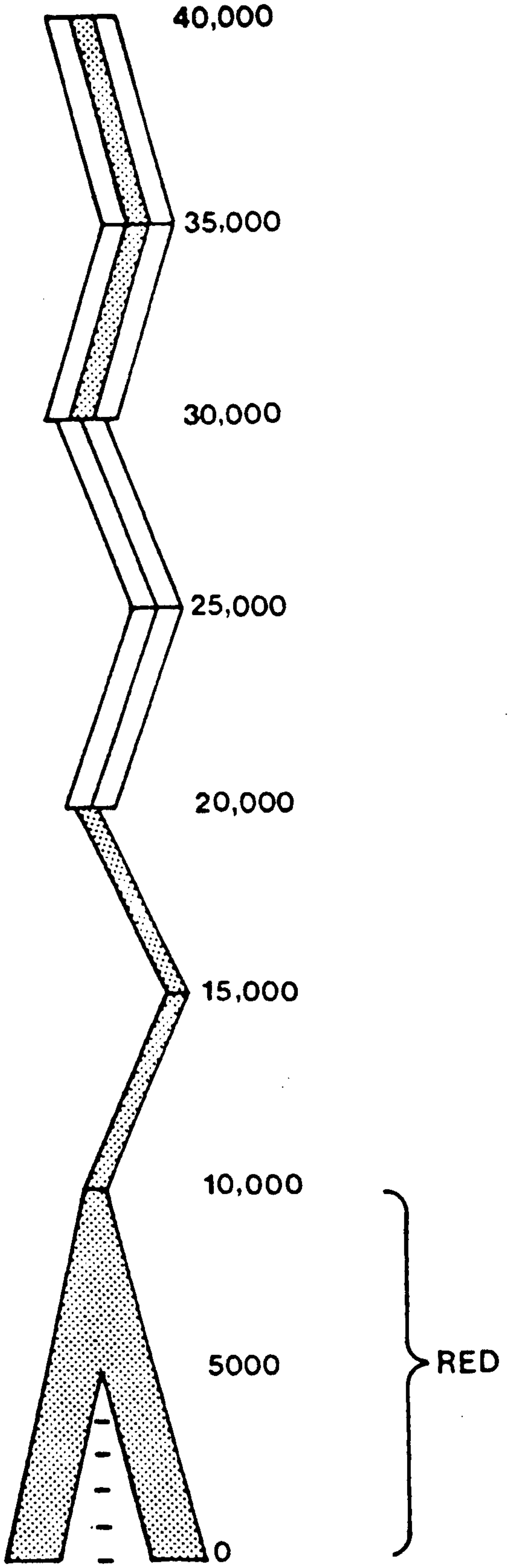


FIG. 10 - SUGGESTED MOVING TAPE FORMAT FOR ALTIMETER

Figure 17

- To format critical control parameters such as airspeed and altimeter for instant unequivocal recognition; design the displays, alphanumerics, symbols and numbers to take advantage of our ability to see objects in degraded lighting at the peak of the human cantrast sensitivity curve, IAW Art Guisburg's recommendations; i.e. design them to subtend 3 to 5 cycles per degree, or about 1/3 to 1/5 the width of your thumbnail held at arm's length.

- To improve cockpit and instrument lighting.

- To initiate efforts to minimize/eliminate canopy glare and reflections.

- To eliminate false horizons.

- To consider establishing a "night-weather role" committee to evaluate proposed aircraft designs and write a design guide.

Maj Art Fowler: Designers need to consider all the night-adverse weather situations; e.g., night-wx formation penetrations, etc. Need to look at the HUD too. Night brightness prevents seeing through it. Haloes and double images prevent reading the symbols.

Maj Gonzales: Putting tapes down the sides of the HUD may worsen that. The first priority is to be able to see the target through the HUD. That's why pilots declutter the HUD.

Dr William Richardson: Suppose we placed the scales Grant proposed along the sides of the HUD, on, say, the support braces? Not enough room?

Col McNaughton: How about on either side of a big Primary Dedicated Attitude Display immediately below the HUD?

Audience: Okay, but what about the up front controls?

Col McNaughton: Could be moved around to the left side of the HUD control panel - for the left hand. Could be molded on a shape to fit the left hand, to provide a stable grip point from which he could type the control keys (Fig 18).

Audience: Discussion - general approval.

Maj Gonzales: The F-16 Simulator is a night visual simulator. You run the simulator a lot brighter than you want to fly at night. That's why we have a negative feedback with them. Also, there's no canopy to create realistic glare and reflections.

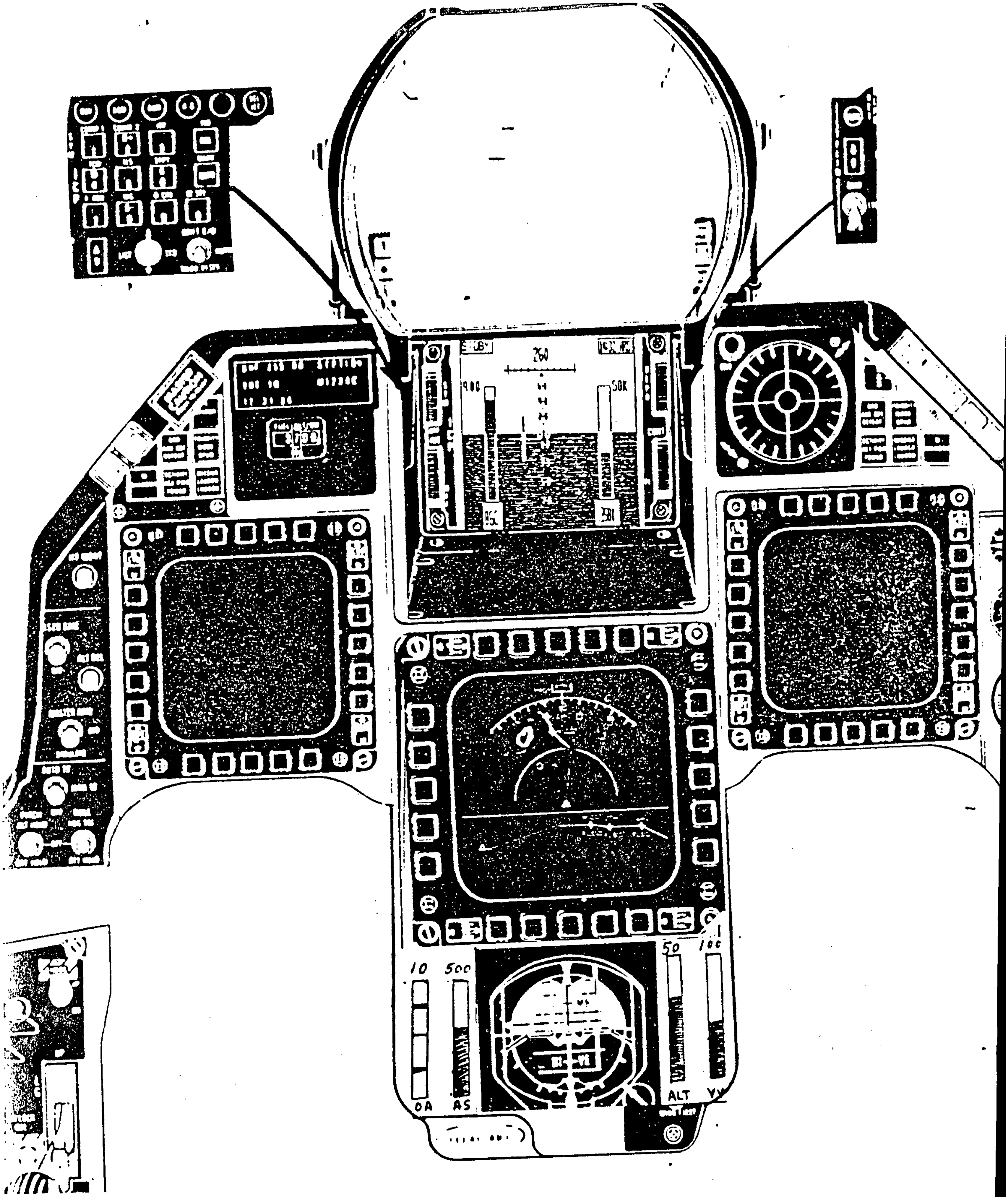


Figure 18

Dr Richardson: Some of your problems could be improved if you required lighting mockups to include a canopy.

Col McNaughton: It's getting late ladies and gentlemen so why don't we begin to wrap things up? I'd like to put up some slides for suggested recommendations.

1. How about improving the HUD for instrument flying.

2. A Primary Dedicated Attitude Display (PDAD) high in the center of the instrument panel or console projecting an attitude display or modified PVHD onto the HUD control panel? (Figs 18 and 19).

Audience: It was considered a good idea with the F-18 and F-15E also, except several did not want it dedicated. They wanted to have the option of a moving map display. With electronics, one could substitute an electronic ADI (EADI).

Lt Col Bill Ercoline: The display is good, but let's not specify what it'll be.

Col McNaughton: Well, I'd like to see what the consensus here is regarding a dedicated attitude display there, like the F-105, F-106 and other aircraft designed to fly in the weather. In fact the SR-71's got two of them.

Maj Fowler: Some of those opposed to dedicated ADIs have already left, but the rest of us agree with you.

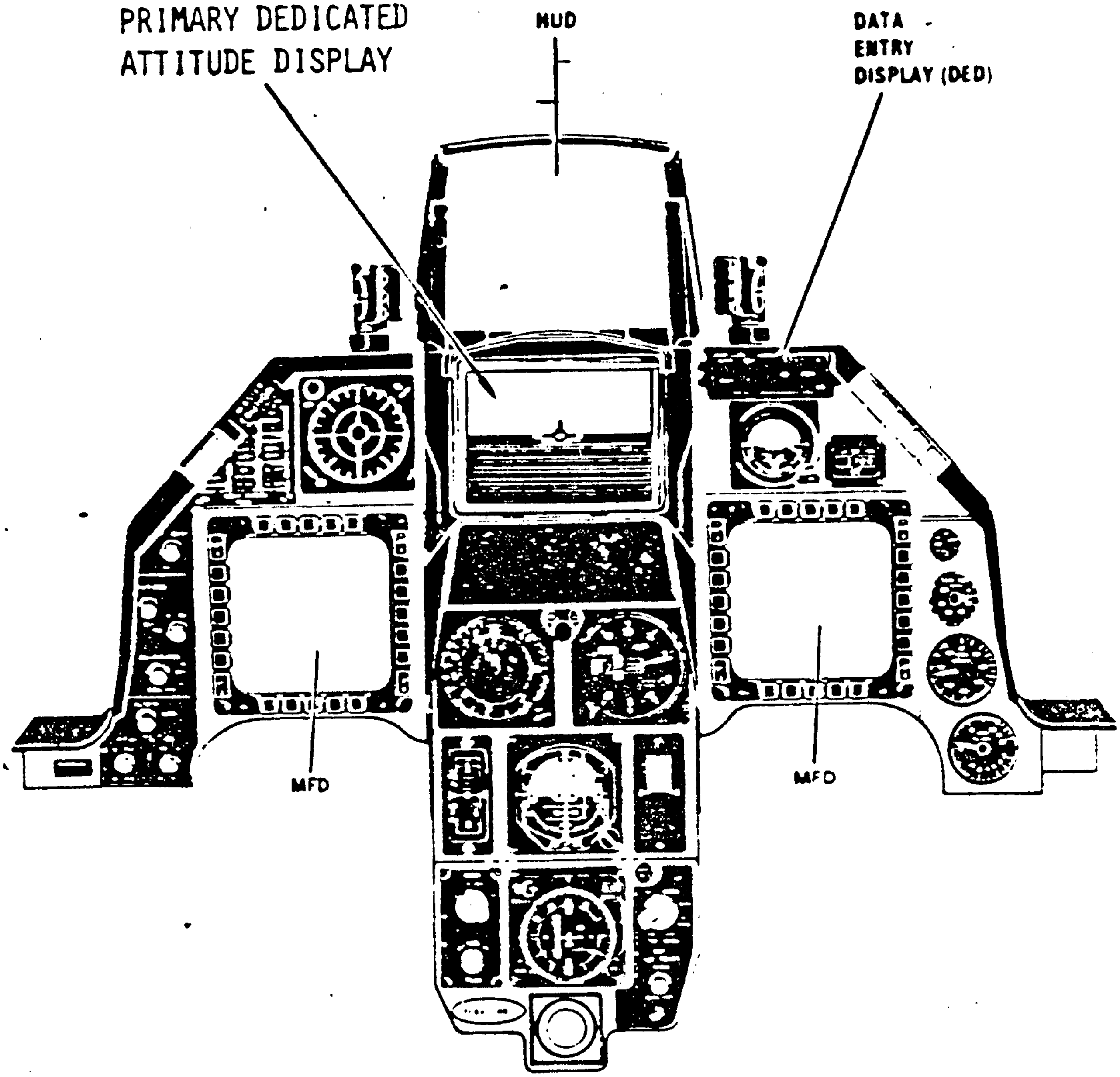
3. How about non-visual cue such as a noise generator on the side of the F-16 to provide an aural cue to airspeed, like a little screw out into the windscreen--that was the suggestion of Col Paul Rost, AFISC/SEFF.

Unidentified: That noise is what saved Col Kehoe in his F-15.

Maj Gonzales: The ECS is so noisy it blanks out all ambient noise.

Col McNaughton: AAMRL is developing technology to counter steady-state noise like engine or ECS--the noise cancelling headset which contains microphones that pick up noise and a system for phase-reversing the signal and playing it back, cancelling about 20 db. Could be accelerated if pushed. Points of Contact: Dr Chuck Nixon and Rich McKinley, (513) 255-3607, at Wright-Patterson AFB.

4. Improved cockpit lighting - as recommended by the cockpit review team including Col Paul Rost, Maj Rooster Rouse, and Maj Dick Frank, at Edwards. Consider using sturdy goose-neck lamps mounted to each canopy rail, as does the SR-71.



C DF

FIG. 2 - PRIMARY UPFRONT CONTROLS AND DISPLAYS

Figure 19

2

5. Reducing canopy glare and reflections: Consider glare shield extensions (frangible in the F-16) or "Bat Wings" folding down from the canopy rails, as in the SR-71.

Maj Gonzales: You'd have to have big bat-wings in the F-16; might block the instruments. How about using micro-louvre directional filters?

6. Radar Altimeter:

Maj Gonzales: CARA is coming and SSG's position is that we're not doing anything till we get CARA. The Air National Guard's position is that they're going to retrofit their F-16 Block 10's with off-the-shelf RAs. We at Hill have been asking for the RA since the first guy hit the ground in 1981. (CARA - Combined Altimeter-Radar Altimeter).

7. For the future aircraft, does anyone disagree with this list, or are there any additions?

Maj Gonzales: I think if we have the technology, the HUD should be built as the primary control instrument. If the technology exists, why not build the HUD to be the primary attitude indicator for the airplane?

Col McNaughton: Well, because you've got the basic problem that:

- Limited FOV: Whereas the ADI provides a 90-110° FOV, the HUD provides only 16-20° which is one-to-one with the world. It's like taking 16° from the ADI and spreading it over the face of the combiner--this not only magnifies the flight path scale (FPS), it magnifies the dynamics such that the FPS does not hold still for interpretation. To recover from a rapid roll or pitch rate on the HUD, you must first stop the roll and pitch rate so you can read/decode the FPS.

- Lack of clear distinction between sky and surface precludes instant appreciation of upright vs inversion, climb vs dive, or about what degree of climb or dive. By its very nature, it can not provide the instant Big Picture. Hence, it's not adequate for the recognition of and coping with unexpected unusual attitudes. The suggestions we've made regarding the HUD (vertex pointer on the FPM and radically changing flight path pattern between climb and dive) might be useful to alert the pilot to go to his primary attitude display and should be tested, but trying to do it all on the HUD while retaining the same earth-referenced scaling of the HUD is not possible.

Maj Gonzales: We're talking about the future now. What we saw this morning where they're going to project the world on this virtual cockpit which you're going to be wearing. It's stupid to build a projection system if I can't fly everything. I need to go head-up. We're talking third generation now; we're talking 15 years from now, probably.

Col McNaughton: Well, I don't know if VCASS will be ready for ATF, so we're talking ATF and possibly some other interim aircraft before we start getting virtual cockpits. But technologies like MAGIC with its 5 CRTs or PCCADS - the big flat instrument panel, may be. What I'm saying is, we need a vertical situation display or attitude display close to the eye, right below the HUD. The HUD calibrates the outside world--it's a vernier scale which is referenced to the earth: it provides the precision for ordnance delivery, close terrain clearance or spot landings--the micropicture if you will. The attitude display is aircraft referenced--gives the instant Big Picture of attitude; by its very nature, it's not a precision instrument but it's not supposed to be; it's supposed to provide the macropicture, to tell him whether he's upright, inverted, climbing or diving and how much at a glance without him having to think about it. It's becoming apparent that you really need them both and need them both in the same general field of regard.

Dr William Richardson: Correct. It's important you get your research going in the Aeromed Lab or wherever, to support the ATF for these specific kinds of conclusions and presentations. You know, we're going to multipurpose displays and to HUDs so you could identify those specific new technologies that look most promising for improving crew station design and the Aeromed Lab people are going on it right now to demonstrate their practicality for this type of an operation. We have a flight simulator here at the base and could bring in pilots, both experienced and nuggets, to get an evaluation based on reality. I think it would be a most useful outcome of this meeting to get that.

Discussion on experience level of SDO mishap victims followed, Maj Gonzales commenting that all levels of experience were represented.

Dr Richardson: I don't think it's a problem unique to our Air Force. I think it's world-wide because we've lost many F-5's. We lost 4 in one month when we sent them over to Iran--those 4 were probably all lost due to loss of situational awareness. It was during Ramadan, that month when people are not allowed to drink water from sunrise 'til sunset, the pilots were dehydrated. It was August, it was hot, and they were flying successive missions, and couldn't drink any beverages. I'd still like to know the experience level of our losses.

Col McNaughton: That's everybody, it's a spectrum of guys, and of course, they're flying at night, they're flying tired, they're flying strung-out, you know; they fly like TAC pilots fly. Anything else to add onto this? Bottom lines?

Dr Richardson: Something to warn the pilot he's out of control or in an unusual attitude. And an autorecovery system.

Col McNaughton: How do we know what constitutes an unusual attitude, unless he's getting ready to hit the ground, which requires a more sophisticated GPWS?

Discussion Garbled: How will a Big ADI prevent CWG?

Col McNaughton: One advantage of the Big ADI is that it reduces the workload of flying in conditions of reduced visibility or in IMC so much that it will free up your attention for other tasks--like maintaining aircraft control and avoiding hitting the surface in the first place, or another aircraft.

Discussion Garbled: Why not invest more time and money on basic instrument training? Training is the bottom line.

Col McNaughton: My answer to that is that you can train guys to cope with terrible design, so why not give them a good design so they can learn to fly instruments more rapidly and easily, thus freeing up more time for learning to use the aircraft as a weapons system? Training is definitely a bottom line, and until we get better designs, it's all we have. The bottom line is that we need to consider how the pilot functions and what he needs in designing the pilot vehicle interface, and what he needs to maintain orientation, and what he needs to recognize and cope with unexpected unusual attitudes. Is there anything more on the design of a basic global view attitude indicator?

Ed Hartman: Well, my name's Joe Bill Dryden and I think with proper training, we can do it all on the HUD. (Laughter)

Col McNaughton: Yes, but you've got 8000 hours in fighters, and you've got eyes like a Chuck Yeager, and you can switch your attention faster than a VHSIC. You'd put a Cray to shame. Unfortunately, there aren't that many Joe Bill Drydens out there. You know we need those guys but they're not always the best guys to be the sole aircraft evaluators of aircraft that will be flown by the ordinary fighter jock. We're all on a Bell-shaped curve and Joe Bill may be out here 3 or 4 standard deviations above the norm. You know, we're all different with different capabilities.

Maj Gonzales: If man is a pattern recognizer, why don't we use the same pattern, especially for the MFDs, for showing attitude references on all of them? You know, when a pilot looks at a cockpit, he looks at the round dial in the center and looks for black or white--that's the pattern. When you look at the HUD, you're going straight line vs dashed line. When you look at the radar in the F-16, you're going Westinghouse W; on straight lines, it's got toe on the ends that point down. You know, I think you need to standardize whatever you say--whether it's going to be chevrons down and straight lines up; we could put another attitudinal reference on all these other MFDs, make it the same throughout, so no matter where I look, the same thing is up as down. Probably the best thing you can do is design the attitude display to be instantly interpreted, so you don't have to figure out what it's telling you.

Unidentified: Why not make a goal to make the HUD an ADI?

Col McNaughton: I don't think that's a goal. I don't think you want to make the HUD an ADI because you want the HUD for killing bad guys and you don't kill bad guys with an ADI. You keep your attitude awareness via the ADI but the HUD's basically a gunsight.

Unidentified: A future HUD may be able to do it all.

Maj Gonzales: Let's not forget, the F-15 can kill other aircraft at night, in the weather, where your tactical symbology in the HUD gives you guidance, while your instruments in the HUD, because of the dynamics of the situation, doesn't give you the time to move your eyes. That's why I'd like to see the HUD give me the same feeling of security I get off of the big round ADI. I'm sure the F-15 driver wants the HUD where he has it. We all have got to be flying the damn HUD at night.

Unidentified: What are you trying to say, Grant?

Col McNaughton: What I'm trying to say is that I think we need 'em both. I think we need the HUD that's a gunsight, that provides the micropicture, and I think we need a dedicated attitude display right below it, right at eyeball level, practically within the same field of view.

Dr Richardson: What's wrong with that? Why don't we do that? Why isn't that a good idea?

Unidentified: We haven't been able to do that because of size of the CRT.

R. J. Stroup, HQ PACAF/SEF: If you put up a flat-panel display and put a touch panel on the front of it, you can have both worlds: a control panel and a display depending on what you want. The technology to do it exists today.

Unidentified: That's a great idea!

Unidentified: Is it dedicated?

Capt William Burgin, USAARL: It's time-sharing, time-limited. He can use it for whatever he wants for a limited amount of time. If he wants his map, he punches his map. After 30 seconds or so, it goes back to ADI.

Unidentified: The French do that on their Mirage follow-on (Rafale); have an MFD immediately below the HUD.

Col McNaughton: Gentlemen, our time's up. I can't tell you how I appreciate the response this afternoon. I'd like to offer a big vote of thanks to Dr Tom Furness for funding this conference and paying the fees of speakers Dick Malcolm and Bo Gehring and to Frank Scarpino who paid most of the rest. Also thanks to Col Krawetz and Bill Augustine. A very special thanks to Kathy Sinkwitz and Evelyn Bailey, my secretary, who performed such monumental preparation and typing tasks; and to Terry Emerson, Lt Col Bob Hendricks, Pete Lovering and his girls; MacAir for sending Paul Summers; Calspan for Terry Lutz; EORD for funding Bob Taylor; Northrop for Frank Watler and Bill Richardson; Lear-Siegler for Bob DeGiorgio; NASA for Dick Haines; GD for Don Gwynne, Joe Bill Dryden and Ed Hartman; the Army, Navy, Marines, Canadians; Dick Newman, Bill Ercoline, Kent Gillingham, Dick Malcolm, Bo Gehring, Dick Geiselhart, Fred Hoerner, Hersh Leibowitz, Dick Haines, Art Fowler, Merrill Beyer, Zack Zayachkowski, Dave Milam, Art Ginsburg, Stan Roscoe, Jeff Craig, Lee Task, Joe Byerly, Don Ross, John Reising, Laurie Hawn, Joyce Iavecchia, Jay Baker, Emily Howard, General DeHart, General Pruden and General Meader, and General McMullen, Dr. Bruce Urbane, Lt. Dan Desjardardins, Lt. Ron Opp, Lt. Kim Mazur, and of course, our banquet speaker last night, Jack Eggspuehler. I won't run through the entire list of 35 speakers and all the people who made this happen, but It sure couldn't have been done without you. Thank you all very much.

COMMENTS REGARDING THE F-16 FIGHTER RELATIVE TO THE AIRCRAFT ATTITUDE AWARENESS CONFERENCE

MAJ Dick Frank
ASD/YPDT
WPAFB, Ohio

Flying at night/in weather, sitting in bubble canopy produces more SDO than in the F-4 or T-38. What causes SDO is the peripheral-vision (PV) motion to the sides in the bubble canopy. Even in daytime-weather, bubble makes it tougher.

Three problems in the F-16:

1. Bubble Canopy - increases your susceptibility to external goings-on. Can't run seat down far enough to block PV inputs.

2. Night-interior cockpit lighting in this aircraft still better than in other aircraft I've flown (F-4 and T-38). I know very few pilots who like to fly at night. Lighting problems identified: would they really use rheostats for every instrument? I could see value to lighting basic instrument group. There is a tendancy for canopy glare from inside lights and from outside lights, which produce false motions. Moving lights can produce SDO.

   A local phenomenon peculiar to Hill is I-80 east of Wendover: approaching it produces the sensation of flying a loop.

   Exterior lights - not optimized for night formation. Designed as DAY-VFR Fighter. The F-4 strip lighting is better. F-16 wing tip missles tend to obscure tip lights. All lights are point sources: there is presently insufficient area lighting to provide the depth perception necessary for flying formation.

3. Relying on the HUD - several problems.

   a. HUD is a good instrument for S & L if you continue to watch it. Too small a view of the world to return to HUD from head-down; takes a while to interpret it.

   b. HUD-IMC - cloud motion the rough HUD produces SDO.

   c. Instrument down X-check: no particular problem except they're deep and require head motion if X-checking with HUD - but if stay head down, OK.

d. SAI too far away to include in instrument x-check.

e. Future move is to cut size of instrument to increase tactical capability/time share - we've shrunk the ADI to bare minimum now.

F-16 makes you more suceptible to SDO than others I've flown.

- Lack of feel cues was not SDO problem for me. Fixed stick does not move - any inadvertant pressure can provoke roll or pitch change. Need rely solely on <u>visual</u> <u>cues</u> to airspeed rather than on audio/wind noise or sluggishness of response.

- No F-16 euphoria or magic carpet effect for me from the bubble canopy.

- View to rear still better than any other aircraft.

- Would like rheostats for basic instrument group: ADI, HSI, Altimeter, ASI, and VVI.

- Canopy glow - yes, it's a problem: going from outside to instruments, etc. Unaware of a solution. If I begin to get SDO'd, I turn up all the lights and go IFR; stop looking outside; of course, tactics must permit that; impossible if flying formation at night. (Best night formation is a 3 mile radar trail.) See no point to fly close in night formation, if radar is working (which it almost always is). That way, lead can maneuver better, and you both can navigate. Flying by radar in the F-16 aircraft is much easier than F-4.

- Map light made with a clip - but there's nothing to clip it to except towel rack. Then can't move it around much. With practice, you can aim it at the basic instrument group.

- DME on HSI - Government Furnished Equipment (GFE) - Warner-Robins. Problem: It's too dim and also too hard to fix.

- Use pencil lights to illuminate knee board.

- We're looking at Radar Electro-Optical (REO) filter/hood. Are working A/B Filter.

  C/D has no REO - uses MFD's. Lighting should be better. Edwards night lighting evaluation on C/D said it was acceptable though there are still canopy reflections. Would include night AAR, bombing, and formation.

- ADI is as small and as low as we'd ever want it to get.

- HUD control panel uses excess prime real estate.

- If put the basic instrument group where the HUD control panel now is, it would be better.

- Trend now is to delete basic instruments in favor of MFD's. I see a real problem. I feel you should always have a dedicated attitude instrument in prime location. As long as the pilot flies the aircraft manually, he needs basic instruments there all the time. Can't see time sharing the attitude indicator.

  1. If get SDO'd would take you longer to realize it.

  2. Once you realize you need the ADI, you've got to call it up; therefore, I think it would be an unusable system.

Many pilots fail to realize how difficult it is to use the HUD as the basic instrument, though they may believe they can.

A high ADI would permit the wingman to sneak a peek, thereby maintaining/regaining his own aircraft attitude awareness.

DEPARTMENT OF THE AIR FORCE
USAF HOSPITAL MISAWA (PACAF)
APO SAN FRANCISCO 96519 5300

Dear Grant;

2 October 1985

1. Thanks very much for inviting me to the conference on Aircraft Attitude Awareness. Needless to say, I would love to attend, however, being this far away, and having just returned from the states three weeks ago, and with a Staff Assistant visit coming up in three weeks, I can't justify coming. Hence the reason for this letter and enclosed package.

2. This package is the "bare bones" outline of a thesis and lecture that I've been pondering for some time. Your invitation prompted me to put it down into print. I also gave an abbreviated form of this to the pilots at McDill after the last F-16 vertigo accident. It represents an analysis of past vertigo accidents in the F-16, with my own inferences as to their real cause, and a proposed training program to avoid such accidents in this aircraft in the future. I have access to data on all the vertigo accidents of both types. I have segregated them into Type I and Type II arbitrarily. The two NATO accidents mentioned are ones that I learnerd about at the Multi-National Safety Group meetings; there may be more.

3. Let me dispose of the Type I vertigo accidents first. There is nothing short of a well-ingrained pattern of frequent attention to the attitude and instruments that will keep you alive in this airplane close to the ground. That is true in any aircraft, but more necessary in this aircraft because of the lack of other cues that you and I have discussed before. Maybe we should hire pilots with built-in metronomes.

4. Which brings us to the classical, active vertigo, or Type II accident. These seem tragically more common in this aircraft than in other aircraft. On the first summary page (all these are printed for you to turn into slides, if you elect to present this), there are five that I would classify as active vertigo accidents. (The one I exclude, which is arguable, is the guy who ran into the ILS antenna at Hahn. This seems to me to be more of a night visual illusion.) All these accidents seem to start with a significant distraction at a critical and vulnerable phase of flight. These distractions all have a highly probable effect of inducing a head movement while the aircraft is simultaneously wandering off the intended flight path, probably at a sub-threshold rate of progression. It is these two factors, coupled with the change in flight conditions which seems to create the vulnerable climate for one of these eventualities. The two European accidents were the same, one an abort off a low level into the clouds, the second a pull-off from a bomb delivery into the clouds. The F-16 factors I think you agree with already.

5. The two enclosed graphs are data sets which I believe strengthen my argument. The first is a complicated plot of what the F-16 actually does if you turn it loose. I have several sets of data for this; the one I have included

here is a moderately bad case; starting in a thirty degree bank level turn, and letting go for thirty seconds. It's a bit hard to read, but short of a four demensional presentation it was the best I could do. The vertical scale is altitude loss starting at 250 feet down to 2,250 feet. The horizontal scale is a change in bank scale, the left side being favorable as it represents a tendency of the aircraft to roll out of a bank. The right side is unfavorable, the bank steepening.

6. The conclusions I draw from these are several:

a. The F-16 seems to have a dihedral effect, rolling out more than steepening.

b. The altitude loss for thirty seconds is nowhere near that which occurs in this type of accident.

c. The degree of dive is also nowhere remotely near the severity of impact angle usually observed in these type of accidents.

d. A physiologic inference: These are all sub-threshold changes in roll and pitch.

7. The second set of data is incidental to my main argument; it represents the actual performance of the F-16 stand-by attitude indicator. I wrote this up as an article in Flying Safety in late 1984, August I believe. This data plot was not printed in the article but shows the essence. In 35 of 50 basic fighter maneuver missions with more than three engagements each, the SADI did not precess out of its' own six degrees of self-erection capability. The few times it did precess, it was of a mild 10-15 degrees of pitch and bank precession. The worst data point is the thirty degrees of bank and thirty degrees of negative pitch achieved. It also frequently precesses out of its' self-erection capability during the air-to-ground range pattern, probably because of the constant one way turns. The point is that it is extremely reliable under the most severe conditions. Taking the worst data point of -30 and a bank of 30, it would be easy to use this as a recovery by putting the aircraft thirty degrees nose high and advancing the power. The F-16, even in a heavily loaded condition will not run out of air speed or ideas while you're interpreting the picture further.

8. I have attempted to diagram a typical flight condition in the first schematic. All flying involves minor correctable distractions. In fact, you could argue that the essence of a cross check is returning periodically to each instrument to see what unobserved displacement had taken place since your last glance. Anyway, looking at lead, checking your map, getting the next figure off the approach plate, even turning around to check the bomb splash results in an aircraft position which is different from the last. A true emergency distraction, of course, makes this worse. Most of the time, when your attention returns to the attitude instruments you calmly and precisely return the aircraft to the intended flight path, usually using a sub-threshold correction.

9. Those situations which progress to death do so by a different mechanism, I think. I have attempted to diagram this in the second schematic. When the uncertainty becomes perceived, the unsure or unpracticed pilot makes a rapid correction, at a supra-threshold rate, which induces some actual, perceived

sensations of vertigo. Now he has not only a conflict between his expectation and the instruments, but a conflict between his expectation, the instruments, and his vestibular sensations. This serves to increase fear, so the next correction, probably compounded by the giant hand phenomenon, is even more rapid, inducing more vertigo, and so on. The central mediator of this process is probably simple panic. Simultaneously, this overwhelming fear is causing the mental processing to break, to slow down, and to obscure normal patterns of response, in short to cancel the pilot's ability to automatically recover from this situation. It thus is a positive feedback cycle, leading to larger and larger erroneous inputs.

10. The question then becomes "how to break this positive feedback cycle." The control theory would have us put an active dampening mechanism into the system as an autopilot can do. However, I know of no active way of dampening out the vestibular sensations, and only two ways of deadening them; first, experience, and secondly, drugs. During all this maneuvering, it is very reasonable to expect the aircraft with positive back stick force to assume a nose-down attitude.

11. My recovery system is patterned after Red Flag. We do exercises like Red Flag to desensitize the pilots to the instinctive and expectant fear they would encounter in the first stages of combat. Few of us ever experience a truly panicky vertigo situation and live to tell about it. But we all have minor degrees of vertigo all the time in this aircraft. A vertigo avoidance and recovery program needs to demonstrate to the pilot:

a. Vertigo sensations do subside rapidly, especially with the head fixed and the eyes focused straight ahead.

b. The aircraft does not assume a dangerous downward vector while the pilot allows his sensations to subside.

c. It is possible to mentally talk yourself out of a dangerous attitude by simple sequential logic.

d. The recovery must be at a slow rate to avoid further vertigo generation.

e. The stand-by indicator does not lie.

f. It is important not to look in the heads-up display, as the data is confusing, and the head movements can only exacerbate vertigo.

12. Thus the exercise I have designed and practiced goes like this: Turn head to look at either the oxygen regulator (right and rear), or the new brake test switch (left and rear), while doing an eyes closed aileron roll. As the roll finishes, snap the head center and open the eyes. Despite the average fighter pilot's desensitization, some minor vertigo should occur through coriolis. Remove the hand from the stick, grasp the "towel rack" and count out loud to five; 1,001, etc. Focus on the main attitude indicator, confirming that the stand-by is in agreement. Consciously interpet the stand-by indicator out loud: "The face is gray, the number is thirty, I must be in a thirty degree dive. The word dive is upside-down, I must be upside-down, etc." Apply smooth, slow

control inputs as in the time-honored unusual attitude recovery sequence. This exercise should be repeated several times to the point where the pilot is comfortable doing this procedure. For safety reasons, it should only be done on a clear day, over land, and with a "B" ship, or with an escort if single ship. If the pilot becomes permanently confused, I recommend a "gyro-out" steer back to level flight. For instance, "roll right slowly, pull up slowly, stop roll, etc." While I've done this many times myself, I've yet to present it to as a formal request here in the Wing.

13. Lastly, I need not reiterate to you the unique aspects of the F-16 which maximize potential for an active vertigo situation. I am also struck by the relative rarity of this type of accident in the F-15. I can only think of one. I am also not aware of any in the A-10, and the rate in the F-106 was several orders of magnitude less than the F-16. Why is another question. I believe the changes in pilot training documented by General D. Hart in his letter of late 1983 to General Doppelt, the then TAC Surgeon, hits that very well. Also, you will remember we do not do unusual attitudes in the F-16 because of the lack of a B model and a hood. Once again, there is no training specifically directed at the vestibular function or the psychodynamics of this problem in Air Training Command or in any aircraft.

14. I apologize for the imprecision of these remarks. I've been thinking about this for some time, but have yet to set it down on paper perfectly. I hope this makes some sense to you and it will be interesting to see if anyone at this conference agrees with this thesis, or has read or published anything of this nature before. I would also like to know what you and the members of this conference think of the idea of a desensitization program.

15. I sure wish I could come and please keep me on your invitation list.

Geoff

GEOFFREY W. MCCARTHY, Maj, USAF, MC
Hospital Commander

P.S. I discovered today that the Main ADI has "Climb" + "Dive" printed only once, and visible to ± 45° of pitch. But, the SADI has both printed twice, visible to ±60-70°, plus a reverse color strip ("black in climb) at the 90° pitch point where it reverses. Minor, but maybe crucial differences. You learn a lot of trivia doing a dozen loops!!!

VERTIGO ACCIDENTS

5 ACTIVE VERTIGO - TYPE I

- OBVIOUS A/C DISPLACEMENT
- SIGNIFICANT DISTRACTIONS
  1) STAN EVAL ON WING (2)
  2) O_2 LIGHT
  3) "PROBLEM" - ON RADIO
  4) BOTH BATTERY LIGHTS
- POSSIBLE INDUCED HEAD MOVEMENTS
  1) CHECK WINGMAN (2)
  2) O_2 REGULATOR TO RIGHT & NEAR
  3) ? BATT LIGHTS DOWN & LEFT
  4) TO LEFT & DOWN, THEN UP TO FIND #1
- CHANGE IN FLIGHT CONDITIONS
  1) INTO CLOUDS (3)
  2) IMMEDIATELY AFTER T/O (3)
  3) CHANGE FROM LEAD TO WING (1)

PLUS 1 BELGIAN, 1 DUTCH
SAME - INTO CLOUDS

WORSE IN F-16 BECAUSE OF:

1) SPARSE AMBIENT CUES
2) DIFFICULT FOCAL VISUAL RECOVERY
3) LACK OF AUDITORY & TACTILE CUES
4) MISTRUST OF SADI (?)

3 INATTENTION TO VECTOR - TYPE 1

ATTENTION WAS:

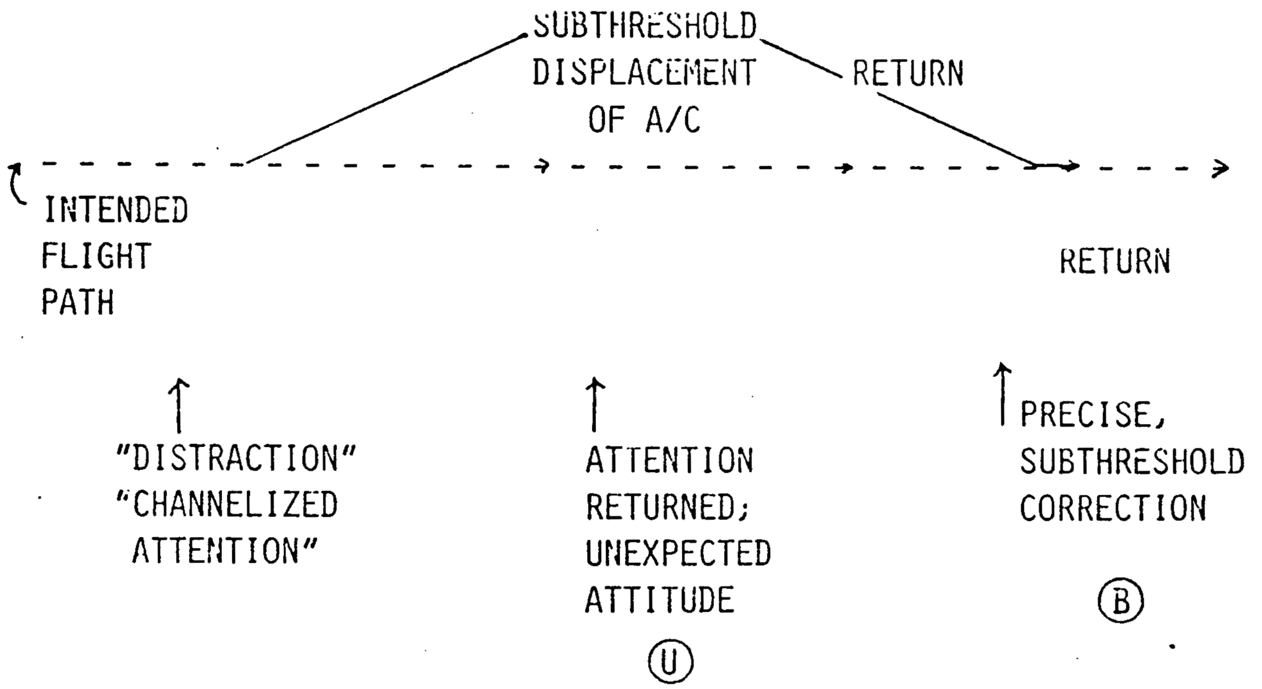
- FOCUSED ON RADAR (1)
- FOCUSED ON GROUND LIGHT (1)
- FOCUSED ON STORES MANAGEMENT SYSTEM (1)

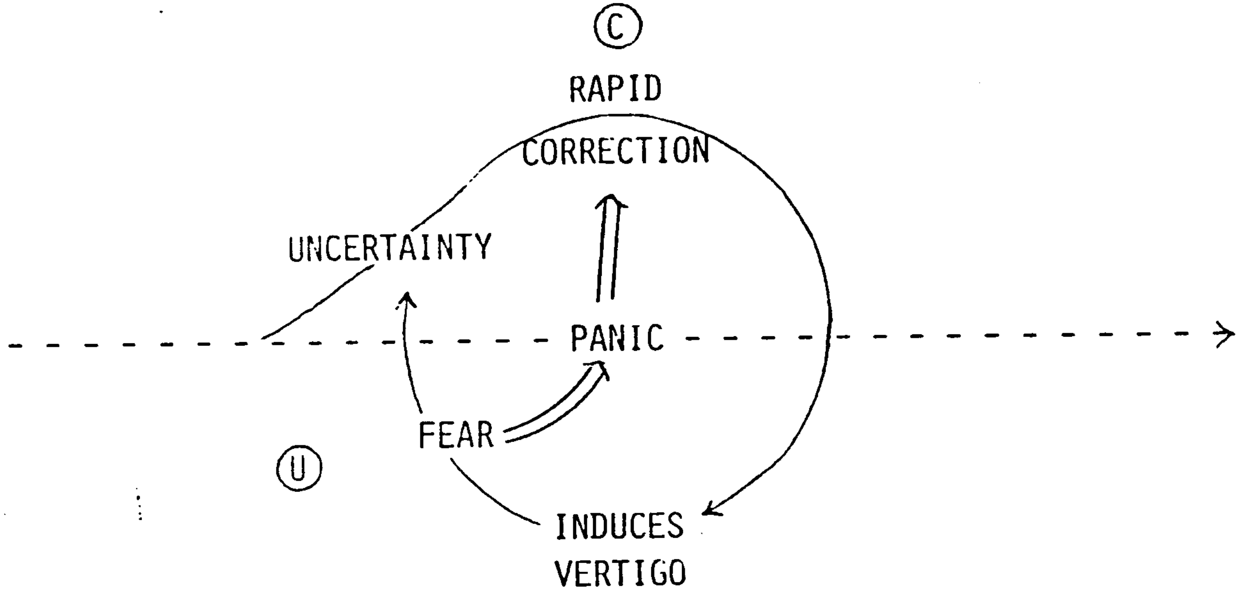
1 NIGHT VISUAL ILLUSION - HIT ILS

WORSE IN F-16 BECAUSE OF:

1) SPARSE AMBIENT CUES
2) LACK OF AUDITORY & TACTILE CUES

MINOR, CORRECTABLE DISTRACTION





- POSITIVE FEEDBACK CYCLE Ⓐ ⟶ Ⓒ
- HOW TO BREAK??

Ⓤ "UNEXPECTED" RETURNS Ⓑ "BENIGN"

OR

Ⓤ "UNEXPECTED" SPIRALS TO Ⓒ "CRASH"

THE CLASSIC FACTORS

- LOW EXPERIENCE
- LACK OF RECENT EXPOSURE
  1) LOSS OF PROFICIENCY
  2) INCREASED VESTIBULAR GAINS

PLUS

- NO UNUSUAL ATTITUDES IN F-16
- NO BACK SEAT HOOD YET
- NO FORMAL DESENSITIZATION PROGRAM
  TO INCREASE FAMILIARITY
  AND DECREASE PANIC

THE VERTIGO RECOVERY EXERCISE

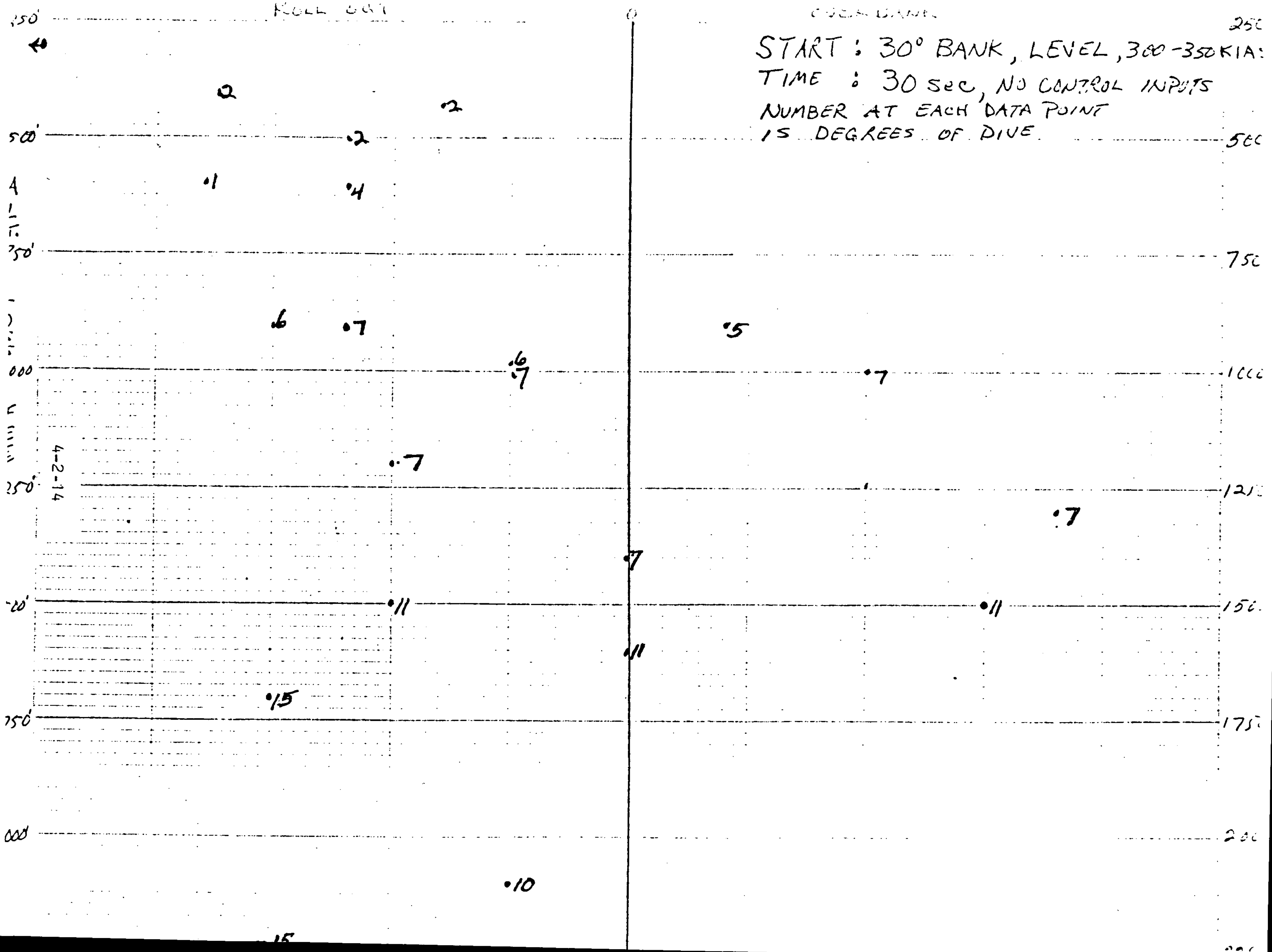
1. INDUCE TRUE VERTIGO BY CORIOLIS
2. WAIT 5 SECONDS
3. ANALYZE SEQUENTIALLY
4. DON'T DISCOUNT THE SADI
5. RECOVER SMOOTHLY

FORMAL PROGRAM

ELEMENTS

1. DEMO A/C DRIFT -
   - A. HANDS OFF 30 SEC
   - B. NOTE ATTITUDE CHANGE
2. THE VERTIGO RECOVERY EXERCISE
   - HARD TO INDUCE REAL SENSATIONS IN FIGHTER PILOTS
   - ELIMINATING VESTIBULAR INPUT CAN ONLY BE DONE <u>PASSIVELY</u>, BY WAITING.
   - HAND OFF STICK (GIANT HAND PHENOMENON).
   - PANIC "JAMS" THE MIND, SO REASON CONSCIOUSLY, SLOWLY, SEQUENTIALLY.

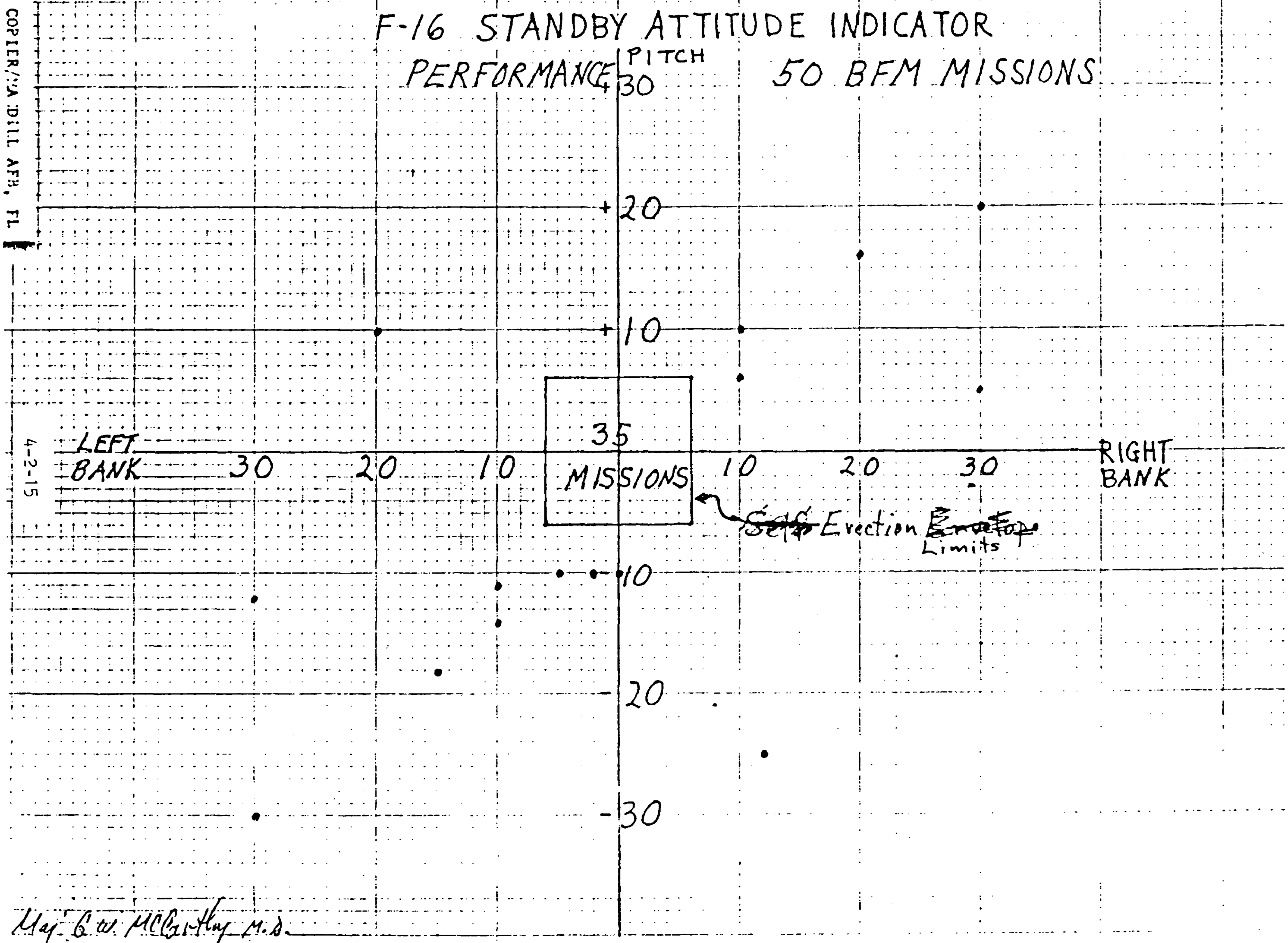
- SADI IS RELIABLE
  - A. ARTICLE IN FLYING SAFETY AUG 84
  - B. DATA PLOT
- SMOOTH, SLOW INPUTS TO AVOID FURTHER SENSORY CONFLICT
- REPEAT FREQUENTLY, USE VTR DEBRIEF.



START : 30° BANK, LEVEL, 300-350 KIAS
TIME : 30 sec, NO CONTROL INPUTS
NUMBER AT EACH DATA POINT
IS DEGREES OF DIVE

F-16 STANDBY ATTITUDE INDICATOR

PERFORMANCE 50 BFM MISSIONS



4-2-15

Maj. C.W. McCarthy M.D.

UNIVERSITY OF WISCONSIN
MADISON 53706

DEPARTMENT OF PSYCHOLOGY
W. J. BROGDEN PSYCHOLOGY BUILDING
1202 WEST JOHNSON STREET

October 23, 1985

Grant B. McNaughton
Col., USAF (MC) CFS
Aeromedical Advisor
Life Support SPO
Wright-Patterson Air Force Base
Ohio 45433-6523

Dear Grant:

Thanks for the crash course (pun intended) on disorientation in the real world. The program was excellently organized. A few suggestions that might help by way of optimizing the match between human capacity and task demands, are enclosed. The vestibular system plays a central role in all aspects of disorientation, especially in vertigo-inducing maneuvers. I would strongly urge that consideration be given to a program of anti-vertigo training. The known adaptability of the vestibular-ocular-reflex is a major point in support of the belief that such a program would work to insulate pilots from vertigo and the disorienting sequela of large and rapid changes in gravitoinertial force vectors.

My first observation and recommendation relates mainly to pilot selection criteria. It seems reasonable to take advantage of the differing specs that human beings have, that characterize certain critical parameters of various oculomotor systems. For example it is a considerable advantage to be able to suppress vestibular nystagmus, for otherwise target acquisition and maintained fixation would be sacrificed. Since this is accomplished by the slow pursuit system, it follows that individuals capable of maintaining pursuit at high target amplitudes and frequencies will also exhibit the greatest range of nystagmus suppression. Why not select for the frequency response with the highest cut off frequency?

My second suggestion relates to training and pilot adaptability. It seems appropriate in light of the large losses attributable to disorientation, to institute a program of rigorous vestibular retraining that exposes pilots to vertigo-inducing force configurations of the type met in actual flying maneuvers. This should be accomplished on a gradual basis, slowly building up appropriate force ~~of~~ vectors and applying Coriolis maneuvers of ~~and~~ gradually increasing amplitude, again building slowly. It is now well established that the vestibular system is an excellent example of a physiological adaptive control system. However, the system adapts with great specificity of frequency, phase and orientation, hence training must range over the entire spectrum of force levels and directions actually encountered in flight.

A similar training program might be established to increase the pursuit suppression of nystagmus which, as described above, plays a crucial role in controlling target fixation during and after vestibular stimulation.

Finally, a third training approach should be established to deal with vertigo-inducing visual-vestibular interactions. This should take the form of adaptation to vection. Here pilots should be exposed to optokinetic patterns rotating and translating around each of the three axes of space. Pattern velocity, the principal parameter, should again be varied in stages from low to high and finally vestibular stimulation should be added to the stimulus configuration.

I believe one cannot overstate the major fact that the vestibular and oculomotor systems that seem to be most central to the disorientation problem are themselves remarkably adaptive and plastic. As such, there is rather compelling support for my view that a great deal of the disorientation challenge can be met right on the ground.

Sincerely,

Sheldon M. Ebenholtz
Professor

pak

VISION TRAINING

David Pannkuk, Designer
Perceptual Dynamics Research
5303 duPont Circle, Milford, Ohio

The purpose of this paper is to propose a set of exercises that will condition and train visual behaviors. The training will result in an ability to see quickly with accurate recognition and responses.

Flying is a special human activity. The quality of flying is based on the ability of the eyes and mind to qualify and respond to flight information. The basic visual habits used in flying are formed away from flying and flying skills are adapted to those habits.

A few pilots will have learned superior visual styles. Those styles are marked by precision, wide visual fields, and smooth responses to flight information.

Other pilots will bring a style marked by disjointed and erratic visual behaviors. The result is uncertainty, doubt, and a lack of confidence in what is seen and responding to what is seen.

Changing flying performance is a must - given current situations. Aifcraft are flying faster; flight information is increasing both in speed and complexity. Avionics designers have not developed a consensus on where and how to place information displays. There is even confusion as to what information should be displayed.

That vision-training is lacking can be found in the descriptions of see-and-avoid situations. The FAA Advisory (AC-90-48C) uses standards of vision that are far too ordinary for current flying requirements.

In addition, an assumption is being make - poorly taken and very misleading - that flight experience is enough to develop vision skills suitable for flying.

If flight experience were enough, why during World War II were pilots required to take vision training? The average speed of aircraft ranged from 200mph to 450mph. The reasoning was obvious: Early in 1942 and 1943, the U.S. Navy pilots were downing aircraft at a ratio of 1:3 (friend : foe) making for a very unhealthy situation. After vision-training was introduced, the ratio became 1 : 99 (friend : foe) - a situation far more becoming.

Flying has its basis in eye-hand coordination. There are programs currently in use that stress physical conditioning as a way to improve eye-hand coordination. There is as much validity in proposing a program that stresses visual conditioning for the same purposes. In fact, in a given situation which would be preferred: A thin pilot who lacks superior vision or a fat pilot with superb visual skills? PDR has designed a computer-based model of superior vision that introduces and develops skills measured in:

- Split-seconds of accurate seeing, recognition, and responses.
- A reduction of inefficient visual habits.
- A wider visual field.

In combination, the skills will be felt in the reduction of:

- errors of judgement.
- poor perception of data and events.
- an inability to comprehend flight information quickly and accurately.

The checklist is offered as a basis and a way to compare. The graphs and charts support the proposal. Tied together, a start can be made to change and improve the quality of vision and flying skills.

Case Study: An Application of Visual Training Technology

Times may change but circumstances don't seem to. Early in WWII, there was a serious problem involving identifying/ recognizing friend from foe. The records will show that for every three planes downed by American pilots/gunners, one was friendly. In the great British raid on Dieppe, 93 British aircraft were lost; 66 were shot down by British gunners. The Japanese pilots made a terrible mistake during the Battle of Midway by failing to recognize the difference between the Grumman Avenger having a rear turret and the Wildcat which did not. The ability to perceive "something's wrong" wasn't present or available.

The table demonstrates the effect of training visual perception. While these figures are taken from U.S. Navy personnel, the training of visual perception was extended across every service where flying was involved. It is interesting to note that the ability of the pilots and gunners in downing aircraft was a 30 : 1 ratio of foe to friend. While many reasons are offered as to why the ratio later changed, it is also interesting to note that visual training was discontinued as early as 1951 and has never been restored.

% of Planes correctly identified	Group One % of Pilots	Group Two % of Pilots
100%	2.5%	12.5%
90%	30.3%	74.7%
80%	66.6%	94.6%
70%	88.9%	99.3%
62%	- -	100.0%
60%	96.6%	
50%	98.8%	
22%	100.0%	
	15 Sessions	50 Sessions

(Each session = 30-minutes)

Ordinary Levels of Visual Field

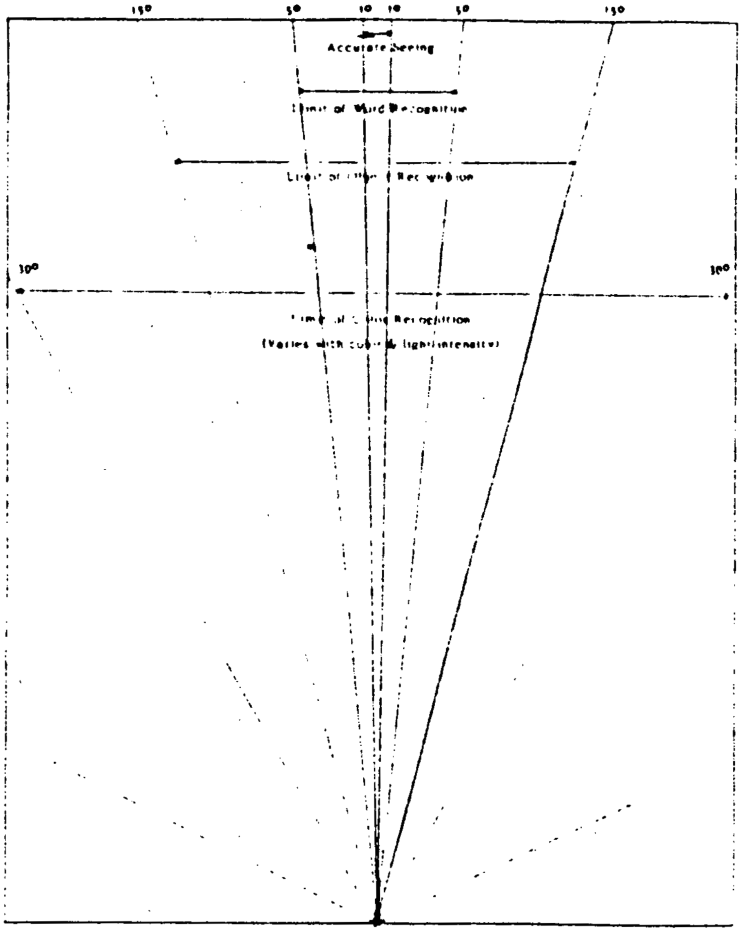
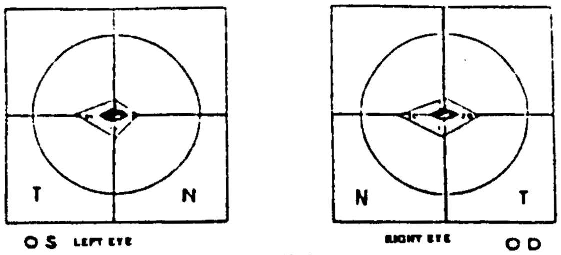


Figure 3 Pre-Training

This describes the "norms" or "averages" of visual field. Descriptions of 2-degree focal vision and ambient or peripheral vision describe learned levels of perception - not trained levels.



SUBJECT G (Refractive/Visual Skills Normal)

Pre-Training

<u>Angles of Vision</u>

Vertical:	Left Eye:	10/15 degrees	Right Eye:	12/15 degrees
Horizontal:	Left Eye:	26/13 degrees	Right Eye:	20/20 degrees

Trained Levels of Visual Field

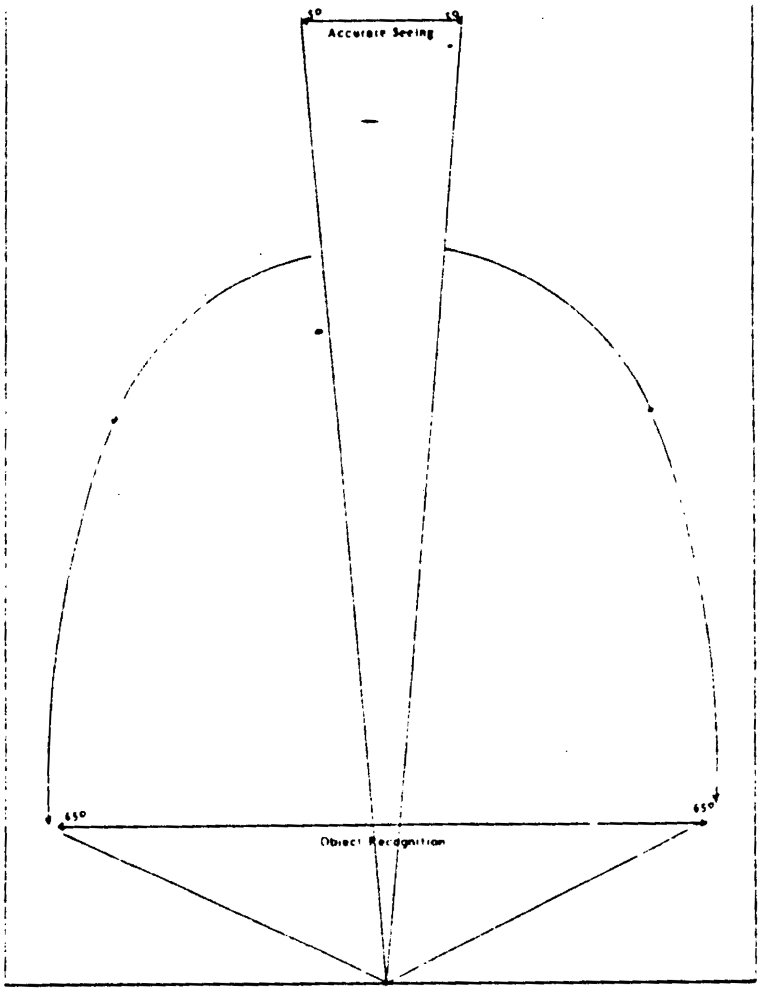
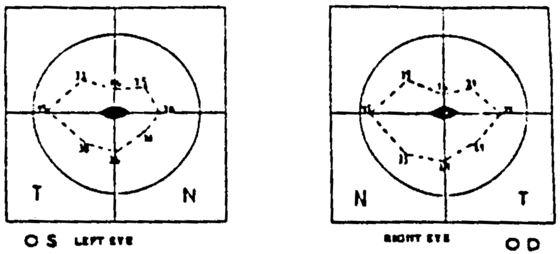


Figure 4 Post-Training

This describes visual field after training. As a result of training, <u>accurate</u> seeing or focal vision was increased by substantial amounts ranging from 200% to 400% over "norms". <u>Object recognition</u> was increased dramatically - from an average of 12° either side of a line of sight to 65° either side of a line of sight.



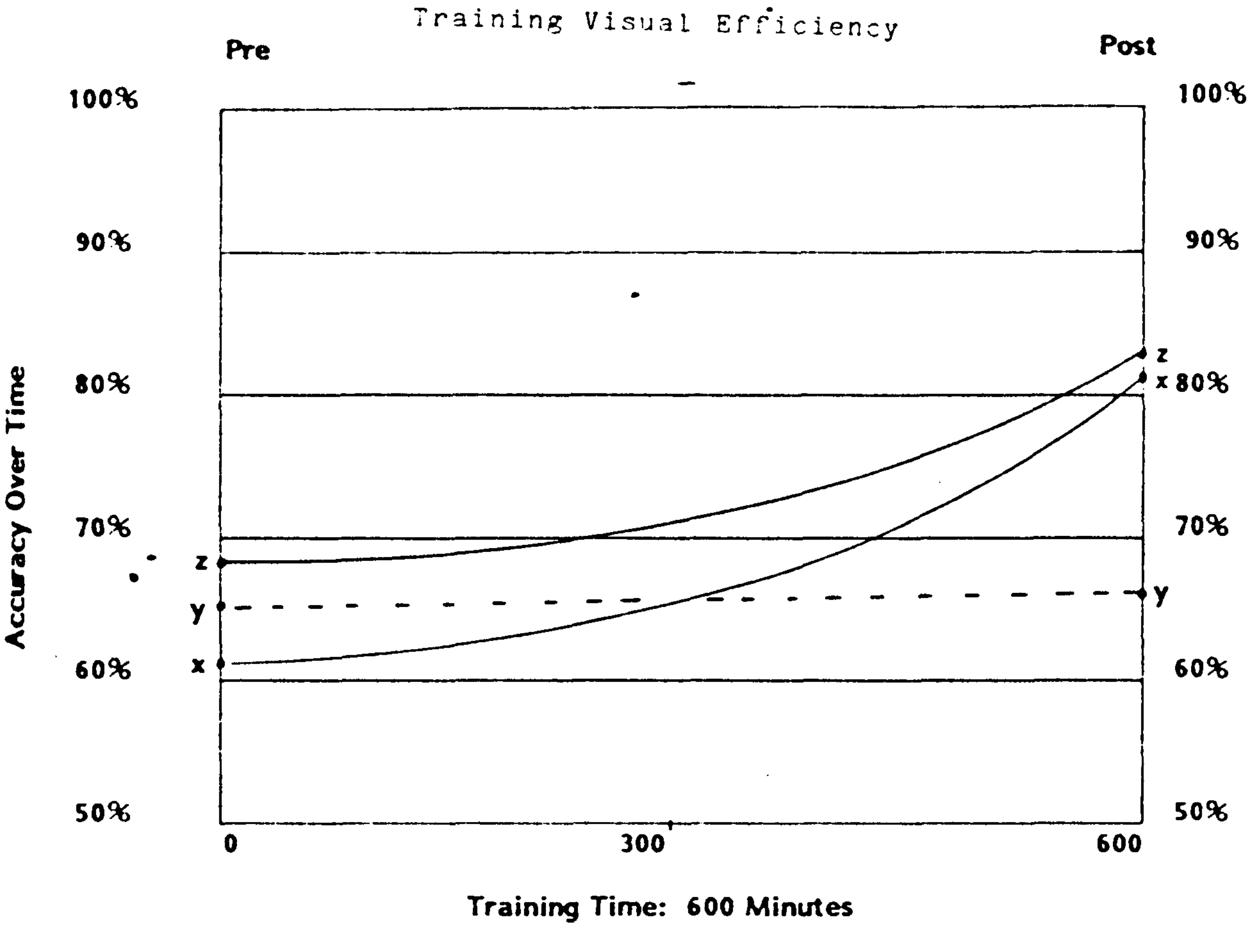
SUBJECT G (Refractive/Visual Skills Normal)

Post-Training

<u>Angles of Vision</u>

Vertical:	Left Eye:	16/26 degrees	Right Eye:	16/29 degrees
Horitzontal:	Left Eye:	45/30 degrees	Right Eye:	45/34 degrees

(*) "Psychological Optics" Ohio State U./OEP



Group Average	Beginning	Ending	% Change
Z	69.0%	83.5%	+ 13.5%
X	62.6%	81.3%	+ 18.9%
Y	64.9%	66.0%	+ 1.1%
Individual Range			
Z	60.5-79.9%	74.7-88.6%	
X	58.6-66.3%	75.3-85.2%	
Y	52.6-75.7%	51.0-78.8%	

Notes:

Group Y did not take the training.

Group Z was described as "above-average" in their work.

Group X was described as "average" in their work.

Visual Efficiency is a ratio of **accuracy over time.**

3900
NAMRL 22

Naval Aerospace Medical
Research Laboratory
Medical Sciences Department
Naval Air Station
Pensacola, FL 32508-5700

7 November 1985

Col Grant McNaughton, USAF, MC
Aeromedical Advisor, Life Support SPO
Air Force Wright Aeronautical Laboratories (AFSC)
Wright-Patterson AFB, Ohio 45433-6523

Dear Col McNaughton,

I want to extend my compliments to you for the excellent organization and conduct of the Aircraft Attitude Awareness Workshop. Attitude awareness (and disorientation) is a problem of major portions ($ and lives) for each of our service communities and I applaud your continuing commitment and interest. The workshop was particularly useful in focusing the attention of the airframe and avionics industry on this problem.

The workshop was quite busy and I didn't get a chance to mention a minor research effort in our lab. We have been evaluating a laser projected horizon indicator (PVHD) with regard to simple compensatory tracking. In one experiment, we compared horizon lengths (visual angle) of 90°, 8°, 90° minus middle 8°, and 90° minus middle 60°. The 90° and 90-8° horizons were significantly easier to track than the 8° or 90°-60° horizons (these two were roughly the same). The differences aren't great but they are consistent and statistically significant. In a second experiment we compared horizon lengths of 30° and 4° (a better estimate of a PVHD and a standard ADI). The 30° horizon was significantly easier to track than the 4° horizon. Both of these experiments were complex and the subjects were usually required to perform another task simultaneous with the tracking task. I am row preparing to wrap up these baseline studies with one final experiment. I would like to compare several horizon lengths which are typically encountered in primary ADI's, standby ADI's, small HUD's, and large HUD's. Several of your comments led me to believe that you might also like to see such a comparison. Can you help me find some basic dimension information? Here's what I would like to know:

(1) Absolute horizontal and vertical size of F-16 HUD plus size of attitude/pitch ladder which is displayed thereon (either visual angle or display size plus distance of pilot's eye to display)

(2) "Ditto" F-18 HUD

(3) "Ditto" F-16 standby ADI

(4) "Ditto" F-18 standby ADI

(5) Any other extra large or extra small ADI's

So far, I have only the following rough, unconfirmed dimensions:

F-16 A/B HUD approx 9^0 (C/D bigger?)
F-18 HUD approx 16^0 x 16^0
F-15 ADI approx 3 in diameter (distance?)
F-16 ADI approx 2 in @ approx 30" from eye

I would be delighted to keep you posted on the progress of this little exercise if you are interested.

Sincerely,

J. MICHAEL LENTZ

AIRCRAFT ATTITUDE AWARENESS WORKSHOP
INVITEE/ATTENDEE LIST

NAME	ORGANIZATION	PHONE
Dr. Robert Alkov	Naval Safety Center	(804) 444-7341
Fred Anderson	ASD/AE	(513) 255-3475
Lloyd Apprill	Lockheed, CA	(818) 847-6857
Ken Armstrong	General Dynamics	(817) 763-1776
Abe Arnold	AFWAL/AAAAS-2	(513) 255-4827
COL Jay Baker	USAF IFC/CC Randolph AFB, TX 78150	AV 487-3635
Finely Barfield	AFWAL/FIGR	(513) 255-3472
Jerry Beaulier CDR USN (Retired)	Sundstrand, Seattle	(206) 885-8328
Dr. Kenneth N. Beers COL USAF (MC) (Retired)	WSUSOM, Dayton	(513) 229-6436
Raymond E. Beverly	DMAAC/DRF	(314) 263-4961
MAJ Merrill Beyer	ASD/TASCO	(513) 255-7925
Dr. Kenneth R. Boff	AFAMRL/HEA	(513) 255-2596
Gordon Bonye	Rank, England	01-302-0271
Earle M. Boone	Northrop, L.A.	(213) 970-8334
Frank J. Brem	Sundstrand	(206) 885-8437
Dr. Richard N. Brenner	General Dynamics Ft. Worth	(817) 763-4582
Bart Brooks	USAF/Hill AFB	AV 458-9540
Lorraine Brown	Perceptual Dynamic Res.	(513) 576-3436
LTC Ken Bruner, USMC	USAF Command Staff Col.	AV 278-2747

CAPT William Burgin III	USAARL, Ft. Rucker	(205) 255-6355
Keith T. Burnette	Burnette Engineering	(513) 878-4501
R. Kevin Burns	ASD/ENECH	(513) 255-5597
CAPT Joseph L. Byerly	3247 Test Sq./Eglin	AV 872-3915
James C. Byrd	ASD/ENASI	(513) 255-4130
Wendy Campbell	AFALC/EREM	AV 785-4707
Dale Carmichael	Smiths Ind., England	(813) 531-7781
Stan Chaffee	ASD/YPEA	(513) 255-4130
Donald R. Chisloghi	ASD/TASE	(513) 255-7503
J.J. Cockburn	Ferranti, UK	31 332-2411
MAJ Larry Cohen, USMC	Naval Command Staff Col.	AV 504-3331
Dr. Keith Collier	AFWAL/CD	(513) 255-3724
D.M. Condra	Condra Aviation	(513) 258-0634
Jeff Craig	AAMRL/HED	(513) 255-7592
George H. Crampton	WSU, Fiarborn	(513) 873-2469
Eric Crawford	ASD/ENECH	(513) 255-5597
Peter A. Crowley	Battelle, Columbus Div.	(614) 424-4743
Darold Cummings	Northrop, L.A.	(213) 970-4183
Nathan Davis	AFLC/NMEE	AV 787-5571
Bob DeGiorgio	Lear Siegler AD 3400 Airport Ave. Santa Monica, CA 90406	(213) 452-6881
B/G (Dr) Rufus M. DeHart	HQTAC/SG	AV 574-7811
LT. D.D. Desjardins	ASD/ENASI	(513) 255-4130
MAJ Stephen Detro	102 TFS Springfield, OH	AV 346-2319

Nick Donelson	Northrop, L.A.	(213) 970-3854
Joe Bill Dryden LTC USAF (Retired)	Flight Test General Dynamics, Ft. Worth	(817) 763-3632
Dr. Sheldon M. Ebenholtz	University of Wisconsin	(608) 262-9884
MAJ Robert Eggleston	AAMRL/HEA	(513) 255-3837
Terry J. Emerson	ASD/AFWAL/FIGR	(513) 255-3644
LTC Bill Ercoline	USAF IFC/OP Randolph AFB, TX 78150	AV (512) 487-5071 AV (512) 652-5071
Jeffrey Ericson	Douglas Aircraft	(213) 593-4425
Mark Ericson	AFAMRL/BBA	(513) 255-3871
Chuck Fabian	ASD/ENECC	(513) 255-2046
David Forman	Grumman Corp.	(516) 575-7421
MAJ Arthur F. Fowler	56TTW, MacDill	AV 968-4581
Jerald Gard	Kaiser Electronics San Jose	(408) 946-3000 x 230
Janice M. Gavern	ASD/ENECH	(513) 255-3122
Dr. Valerie Gawron	CALSPAN	(716) 631-6916
Bo Gehring	Bo Gehring Assoc. Toronto	(416) 922-1935
Dr. Kent K. Gillingham	USAFSAM/VNB Brooks AFB, TX 78235	(512) 536-3521 AV 240-3521
Dr. Arthur P. Ginsburg	Vistech Consultants Inc.	(513) 426-4822
LT Dave Gleisner	NAVAIRSYSCOM/AIR5313X	AV 222-7486
Lisa L. Glover	ASD/ENECC	(513) 255-6920
MAJ Gary M. Goebel	VSAP AGOS, Hurlburt	AV 872-7371
MAJ Hal Gonzales	388TIW/SE, Hill	AV 458-2983

MAJ Gary L. Griffith	USAF IFC, Randolph	(512) 652-5071
LTC James H. Ground	836AD/SE, Davis-Monthan	(602) 748-5558
Fred E. Guedry	NAMRL NAS Pensacola, FL	(904) 452-2541
Don R. Gum	AFWAL/FIGD	(513) 255-4618
Donald Gwynne	General Dynamics	(817) 763-2301
Dr. Richard F. Haines	NASA-Ames, Moffett Field	(415) 694-5719
Michael J. Hanley	Battelle Columbus	(614) 424-5070
Ed Hartman	General Dynamics	(817) 763-3320
MAJ Laurie D. Hawn	CDN Forces, Cold Lake	AV 628-6531
Robert Hayes	Jet Electronics	(616) 949-6600
COL Roger J. Hegstrom	AFWAL/FJB	(513) 255-3031
Chuck Helton COL USAF (Retired)	Rockwell International Dayton	(513) 461-4323
CAPT Bob Hesselbein	TAC	AV 432-7746
Thomas A. Hiteman	ASD/YPEC	AV 785-3848
David Hoagland	ASD/ENECC	(513) 255-2840
Fredrick C. Hoerner	USN/NATC	AV 356-4157
Roy Holmes	GEC Avionics	(513) 224-1110
LT J.M. Hooper	HQNAVAIRSYSCOM/APC205	AV 222-1560
Emily Howard	UCLA/MacAulay Brown	(213) 825-4061
Ed Hughes	ASD/ENECH	AV 785-3848
Helene P. Iavecchia	Analytics	(215) 657-4100 X 166
Joyce H. Iavecchia	NADC, Warminster, PA	(215) 441-1499
MAJ Richard T. Island	USAFSAM, Brooks	AV 240-3365
Larry Ivey	ASD/YPEC	(513) 255-3848

Dr. Richard Jensen	Ohio State Univ.	(614) 422-1116
Robert Johnson	Raytheon	(513) 254-3571
Art Kennedy	Garrett Manufacturing Rexdale, Ontario	(416) 675-1411
Thomas L. Kingery LTC USAF (Retired)	Systems Research Labs, Inc.	(512) 736-0595
COL (Dr) Kenneth Klint	WP Med Center/SGP	(513) 257-4234
LTC Arthur Kramer	ASD/YPS	(513) 255-8783
COL Barton Krawetz	AFWAL/CC	(513) 255-5508
Dick Krobusek	Texas Instruments	(214) 343-7982
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Dr. Herschel W. Leibowitz	Penn State Univ.	(814) 238-6008
Dr. Mike Lentz	NAMRL, Pensacola, FL	AV 922-2541
LTC Michael W. Lichty	TAF/SEF, Langley	(804) 764-7031
LTC James Mike Livingston	ASD/XRF	AV 785-6395
LT Carl S. Lizza	AFWAL/CCU	(513) 255-8253
Terry Lutz	Calspan, Buffalo, NY	(716) 632-7500 X 5569
CAPT Tom McCleary	2nd Tac Fighter Training Squadron, Tyndall AFB, FL	AV 970-2951
Tom McClosky	ASD/ENECC	(513) 255-0920
Dr. Grant R. McMillan	AAMRL/HEF	(513) 255-7585
COL Grant B. McNaughton	ASD/AESA	(513) 255-5822
Dr. Richard Malcolm	Maltech Research Oakville, Ontario	(416) 844-9792
Steve Markman	AFWAL/FIGD	(513) 255-3853
MAJ Britton L. Marlowe	Hq. AFISC/SEL	AV 876-3458

Conrad Martinez, Jr.	AFWAL/FIAC	(513) 255-5617
COL John M. Marvin	AFISC/RF Norton AFB CA 92409	AV 876-7251
CAPT Michael Masi	AFWAL/FIGD	(513) 255-3853
COL Gary W. Matthes	6510 TW/Edwards	(305) 277-4230
B/G (Dr) W.L. Meader	AGLC/SG	(513) 257-6632
Paul Metz	Northrop, L.A.	(305) 277-6555
COL David Milam	AF/RDQE	(202) 695-6994
William F. Miller	NATC	AV 863-2794
Jack Moore	McDonnel Douglas	(314) 234-1043
Tom Moore	AFAMRL/BBA	(513) 255-3871
Dr. Reed Morgan	AFWAL/AAAS-Z	(513) 255-4827
MAJ Gary R. Morphew	HQAFISC/SEFF	AV 876-3888
Gerald L. Muehlberger	USAFE	AV RAF Lakenheath Bill
W.F. Nash	J.E.T. Electronics	(513) 399-5917
Frank Neuperger	Maltech Research Corp. Canada	(416) 844-9782
Dick Newman	Crew Systems, Dayton	(513) 372-6395
CAPT (Dr) Mary Ann Orzech	AAMRL/BBP	(513) 255-3122
Robert Pangburn	ASD/TAEE	(513) 255-4217
David Pannkuk	PDR, Inc. Cincinnati	(513) 576-3959
MAJ James C. Parry	AFISC/SEFB	(714) 382-2226
J. Ray Pastor	Lockheed	(818) 847-7051
MAJ John C. Pellosie	AAMRL/HEG	(513) 255-8012

Paul Pencikowski	Northrop, L.A.	(213) 970-4446
CAPT Greg Pixley	ASD/YPEX	AV 785-2929
LTC (Dr) James Popplow	DCIEM, Toronto	AV 270-4101
MAJ Glenn Price	PACAF/DOO	(808) 449-9916
MAJ Ron Price	ASD/YPS	(513) 255-3783
B/G Albert L. Pruden, Jr.	AFISC/SE, Norton	AV 876-2302
LTC Lorenzo Pugh	HQUSAFE/DOO	AV 430-6971
LTC Dick Reynolds	6510TW/TEVI Edwards	AV 350-0668
Gary E. Riccio	SRL	(513) 258-3963
Dr. William T. Richardson	Northrop, L.A.	(213) 942-5159
Dr. Stan Roscoe	NMSU, Las Cruces, NM	(505) 646-1408
LTC Don Ross	AFWAL/FII	AV 785-2060
Michael E. Rountree	HQTAC/DOTF, Langley	AV 432-7746
Dr. Hank W. Ruck	Hq. AFISC/SEL, Norton	(714) 382-3458
COL William Runkle	HQAFISC/SEL, Norton	AV 876-3458
Greg Schoteener	USAF/ANG	(513) 255-5054
Noel Schwartz	AFWAL/AAAT	(513) 255-7661
J.P. Senechal	AFLC/MI-CN	AV 785-2018
Dr. James Sheehy	NADC, Warminster, PA	AV 441-2634
Tony Sheets	John A. Sheets Designs, South Pasadena, CA	(818) 799-1244
Primus J. Shumotz	ANGSC/SGP Andrews AFB, MD	(301) 981-4314
Lawrence W. Smith	McDonnel Aircraft	(314) 232-6257
William G. Smith	HQAAC/IGF Elmendorf AB	AV (317) 552-4730

Johnnie Stegemoller	General Dynamics Ft. Worth	(817) 763-2165
Tom Stoffregen	AMRL	(513) 255-2894
R.J. Stroup	Hq. PCAF/SEF	AV 449-6932
Paul Summers	McAir	(314) 232-3393
Dick Swartzel	AFWAL/FII	(513) 255-2060
Manuel H. Tapia	General Dynamics	(817) 763-4582
Dr. H. Lee Task	AAMRL/HEF	(513) 255-8739
Ray Taylor	Garrett Manufacturing	(416) 675-1411
Dr. Robert M. Taylor	RAF Institute of Aviation Medicine Farnsborough, UK	0252-24401 X4302
Tim Taylor	GEC Avionics	(513) 226-1110
Patricia A. Terrill	ASD/SEG	(513) 255-4433
S.A. Thompson	Northrop, Aircraft Div Advanced Crew Station Development	(213) 970-8112
Jose L. Ubinas	ASD/ENECC	(513) 255-2046
Juris Upatnieks	Environment Res. Insto. of Michigan, Ann Arbor, MI	(313) 994-1200
CAPT (Dr) Bruce C. Urbanc	ASC/AEBA	(513) 255-2479
COL Larry Van Pelt	ASD/EN	(513) 255-3208
MAJ Dennis Vargo	HQAFRES	AV 468-5433
LTC Erik K. Vermulen	AAMRL/IIEX (CAT)	AV 785-7600
Don Vetter	Jet Electronics	(616) 949-6600
John Wagner	AFSL/XRB/Andrews	AV 858-4265
Harry Warelzewski	Sperry/ABQ	(505) 822-5524

Debbie Warner	MacAulay Brown, Inc.	(513) 426-3421
Rick Warren	AAMRL/HEF	(513) 255-8762
Billy J. Watkins	Watkins Assoc.	(513) 667-5119
Frank Watler	Northrop	(213) 942-3924
Martin Wehervich	Hughes	(713) 643-9900
James Welch	Hq. ATC/SE	AV 487-6817
COL A.J. Wilson	ASD/AE	(513) 255-5933
Bill Wilson	ASD/ENASI	AV 785-4400
Alex V. Wolfe	General Dynamics Ft. Worth	(817) 763-3531
Robert Yarow	Cdn Forces DCIEM, Toronto	AV 270-4101
Robert Yeager	AFWAL/FIGD	(513) 255-8298
Bill Yri	ASD/AES	AV 785-5659
CAPT David Zayachkowsky	198TFS, Puerto Rico	AV 860-9233

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