CR 86220

V

[redacted]

POLHEMUS NAVIGATION SCIENCES, INC.

P.O. BOX 1011; BURLINGTON, VERMONT; 05401; PHONE 802 658-1458

PNSI-TR-69-0301-III

NAVIGATION/TRAFFIC CONTROL STUDY FOR V/STOL AIRCRAFT

(Final Report)

VOLUME III - APPENDICES

March 1969

Prepared under Contract No: NAS-12-2024
by
POLHEMUS NAVIGATION SCIENCES, INC.
Burlington, Vermont
(formerly: Ann Arbor, Michigan)

for: Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

Polhemus Navigation Sciences, Inc. was awarded a contract by the National Aeronautics and Space Administration to conduct a study entitled "Navigation/Traffic Control Study for V/STOL Aircraft" (NAS-12-2024). The goal of the study was to provide recommendations to NASA regarding the solution of domestic air traffic control/airborne navigation problems envisioned for 1975-1985. The program was sponsored by the Navigation and Guidance Branch, Electronics Research Center, Cambridge, Massachusetts. Mr. J. R. Coonan served as Technical Monitor for NASA/ERC. Principal investigator for PNSI was Mr. Thomas T. Trexler.

This three-volume final report presents summary results of the NAVTRAC study covering project activity from August 1969 through March 1969. It describes a broad-scope analysis which identifies, from the pilot's viewpoint, the desirable performance characteristics of an advanced navigation/traffic control system for aircraft operating in an environment consisting of V/STOL, CTOL-jet, SST, and general aviation aircraft. A number of recommendations are made for the immediate further research and development of technology related to future airborne avionics systems and air traffic control. The recommended development program has a two-fold design objective: validation of the "Flight Plan Reference/ATC" concept and verification of the effects of automation on pilot workload. Recommendations are made for development of technology associated with NAV SAT and ground-based hyperbolic systems. They include: development of a digital software computer program; man-machine simulation(s) for VTOL and general aviation aircraft; hardware bench and field tests; and qualification flight tests.

The assistance of the following individuals who contributed substantially to the preparation of this document is acknowledged:

Mr. William L. Polhemus	Operations Consultation
Mr. Donald W. Richardson	Engineering Direction
Mr. Linus E. Lensing	Technical Editing and Publication
Mr. Edwin McConkey	Radio Systems Engineering
Mr. Eric H. Bolz	Radio Systems Error Analysis
Mr. Steven C. Lesak	Pilot Workload Studies

ABSTRACT

The Navigation Traffic Control Study for V/STOL Aircraft (NAVTRACS) develops recommendations for the further research and development of air traffic control/navigation related technology. The desired performance characteristics of an advanced navigation/air traffic control system for the 1975-1985 domestic air transportation environment are developed from the cockpit viewpoint. V/STOL, CTOL-jet, SST, and general aviation aircraft are considered. The advanced system embodies two new concepts: a Flight Plan Reference System and Limit Logic. The concepts assume the availability of area navigation aids. Five candidate systems are evaluated: NAVSAT, ground based hyperbolic (Decca, Loran C and Omega) and rho theta integrated with course line computer.

Enroute, terminal area and approach and landing requirements are considered. Area navigation, in this context, provides two capabilities: required horizontal position information for the pilot, and ATC system-required surveillance information. To generate the precision required for approach and landing of carrier aircraft, a differential NAVSAT and/or ground based hyperbolic capability must be incorporated into the system if individual runway instrumentation is not to be used.

Acceptability of each area navaid is evaluated through use of comparative pilot workload analysis. For purpose of this study, the pilot workload approach is used to determine desired system level(s) of automation. Detailed Event Sequence Diagrams which cover both VFR and IFR operations define the pilot's tasks of navigation, communication, aircraft control, and system monitoring. . . . . and show the interface between airborne system and ATC. To insure a broadly based workload assessment, several configurations of general aviation and air carrier-type avionics systems are included in the tradeoff analyses.

Volume I of the report contains an overall summary of the results of the study. Volume II (Technical) discusses the technical approach used in the study and describes the results of various tradeoff analyses which lead to the reported conclusions and recommendations. Volume III (Appendices) documents the background technical data generated to support the analyses and system definition.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Appendix D
PILOT WORKLOAD ANALYSIS

Appendix E
NAVTRACS GROUND AND AIRBORNE SYSTEM COSTS

Appendix F
CANDIDATE NAVIGATION SYSTEMS

TABLE OF CONTENTS (Continued)

APPENDIX F (Continued)

TABLE OF CONTENTS (Continued)

Appendix G
PILOT WORKLOAD ANALYSIS FOR NAVIGATION MANAGEMENT OF GA3 AND AIRCARRIER AIRCRAFT

Appendix H
NAVIGATION MANAGEMENT WORKLOAD ANALYSIS, GA1 AND GA2

Appendix I
NEW TECHNOLOGY

LIST OF ILLUSTRATIONS

APPENDIX A

LIST OF ILLUSTRATIONS (Contd)

APPENDIX F

APPENDIX H

LIST OF ILLUSTRATIONS (Cont'd)

APPENDIX I

LIST OF TABLES

APPENDIX B

APPENDIX C

APPENDIX D

LIST OF TABLES (Cont'd)

LIST OF TABLES (Cont'd)

APPENDIX H

LIST OF SYMBOLS AND NOMENCLATURE

o Arabic Letter Listing (lower case)

a	aircraft acceleration
a	radius of the earth
a/c	aircraft
ackn	message acknowledgement
c	speed of light
d	distance from calibration point to user
d	distance from transmitter to user
dm	distance between point of closest approach and transmitter
do	distance between aircraft and point of closest approach
do	calibration point
dP	position error vector
d rms	rms statistic of radial repeatability error
dT	TD error
f	carrier frequency (mHz)
f k Hz	carrier frequency (kHz)
f	frequency
f30, f31	frequency code of third (3) approach path (outer and inner marker beacon)
g	earth gravitational acceleration
g	general aviation aircraft density
g1, . g14	general aviation candidate navigation systems
h	altitude
hn1, hn2 . . hn3	altitude of the final approach waypoints
ho3, hi3, ho3	command altitude at outer, inner marker beacon and pad, respectively; for the third (3) approach path
$\underline{n}$	rms noise field strength.
$\bar{s}$	horizontal distance in VOR cone of silence
s_h	an altitude
s_{at}	an along track distance
s_{ct}	a cross track distance
s	LaPlace operator
t_a	along track separation
t_c	time delay due to propagation over the earth
v1 . v10	aircarrier candidate navigation systems

o Arabic Letter Listing (caps)

A	heading
ABBR'	abbreviated report
AC	aircarrier
Ackn	message acknowledgement
ADF	automatic direction finder
AFCS	automatic flight control system
A-G	air-to-ground
AIREP	air report
AILS	advanced instrument landing system
AP	autopilot
ARINC	Aeronautical Radio, Inc.
ARSR	air route surveillance radar
ARU	attitude reference unit
AS	airspeed
ASDE	airfield surveillance detection equipment
ASR	airport surveillance radar
ATA	Air Transport Association
ATC	air traffic control
AT	along track
ATIS	automatic terminal information service
ATT	attitude
ALT	altitude
B	TD receiver constant (rad/sec)
Bw	bandwidth of receiver r.f. section (Hz)
CAS	collision avoidance system
CAS	calibrated airspeed
CAT I, CAT II, CAT III	category or landing conditions
CCC	communication, command and control
C/D	control/display
Comm	communication
CPU	central processing unit
CRT	cathode ray tube
CT	cross track
CTD	cross track distance
CTOL	conventional takeoff and landing
CLC	course line computer
CLR	clearance
CW	continuous wave

o Arabic Letter Listing (caps) - (cont'd)

D	operator transportation lag
D	distance
DA	drift angle
DG	directional gyro
DI	deviation indicator
DIST	distance to go
DOC	direct operating cost
DR	dead reckoning
D rms	rms statistic of radial predictability error
DD rms	rms statistic of radial TD system error
DTD	differential time difference
DTD (GB)	differential time difference - ground based
DTD (NS)	differential time difference - navigation satellite
DTG	distance to go
DME	UHF distance measuring equipment
E	east
E	rms field strength
Eg	rms ground wave field strength
Es	rms sky wave field strength
EET	estimated enroute time
ESD	event sequence diagram
ETA	estimated time of arrival
FAA	Federal Aviation Administration
FL	flight level
FPA	flight path angle
FSS	flight service station
FSK	frequency shift keying
G	transformation matrix
GA	general aviation
G-A	ground-to-air
GA1, GA2, GA3	classes of general aviation aircraft (p 2-11)
GDOP	geometric dilution of precision
GBTD	ground based time difference
GMT	Greenwich Mean Time
GS	landing system glideslope
GS	ground speed
HDG	heading
HF	high frequency
H1, H2, H3	hold waypoints
H(s)	transfer function of receiver tracking loop
HSD	horizontal situation display
HSI	horizontal situation indicator
IAS	indicated airspeed
ID	identification
IFR	instrument
ILS	instrument landing system
IMB	inner marker beacon
IMC	instrument meteorological conditions
IMU	inertial measurement unit
INS	inertial navigation system
IP	intercept point
IRU	inertial reference unit
JFK	John F Kennedy International Airport
K	operator gain
K	propagation constant
KCAS	knots, calibrated airspeed
KTAS	knots, true airspeed
Lg, Long	aircraft longitude
Lg_D	waypoint or destination longitude
Lg_o	estimate of aircraft longitude
Lt, Lat	aircraft latitude
Lt_D	waypoint or destination latitude
Lt_o	estimate of aircraft latitude
LGA	La Guardia Airport
LF	low frequency
LN1, LN2, LN3. .LWP1 .	groundpoints or waypoints which define a final approach path
LOC	landing system localizer
LOP	line of position
LOS	line of sight
LWP1, LWP2, LWP3 ..	waypoints which define a final approach path (used with LN1, LN2)

LIST OF SYMBOLS AND NOMENCLATURE (continued)

o Arabic Letter Listing (caps) - (cont'd)

MAA	maximum acceptable altitude
MBR	marker beacon receiver
MEA	minimum enroute altitude
MMD	moving map display
MOCA	minimum obstruction clearance altitude
MRA	minimum reception altitude
M/S	master/slave combination
N	north
N G	navigation and guidance
Nr	number of VOR radials
NAV SAT	navigational satellite
N^2	noise power spectral density
N_p	peak noise voltage
NAVTRACS	Navigation Traffic Control Study
N_A	number of instantaneous users requiring service
NAV	navigation
NOTAMS	notices to airmen
OMB	outer marker beacon
OP	operate mode
P	potential candidate airport for ATC
Pe (s)	phase of the error signal
Pi (s)	phase of the input signal
Po (s)	phase of the output signal
Pr	radiated power (db above one kW)
Pss	steady state phase error
PAR	precision approach radar
PF	position fix
POS	position, latitude, longitude
PPI	pulse position indicator
PT	procedure turn
PVOR/PDME	precision VOR/precision DME
PWI	position warning indicator
Q (s)	position output of inertial platform
R	horizontal distance to a VOR facility
R	general aviation reliever airport
Ro	initial range to waypoint
Rp (d)	spatial autocorrelation function of predictability error
Rr (d)	spatial autocorrelation function of repeatability error
Ro	earth radius
Rpt	report
R/T	receiver/transmitter
RTE	route
RVR	runway visual range
S	south
S	rms signal field strength
Sp	peak signal voltage
SID	standard instrument departure
SID	sudden ionospheric disturbances
SIGMET	significant meteorological conditions
SOP	surface of position
SSR	secondary surveillance radar
SST	supersonic transport
STD	standard
STOL	short takeoff and landing
(T)	airport with ATC tower
T, t	time
Tk	track
To, to	initial time
TAE	track angle error
TAS	true airspeed
TD (GB)	time difference - ground based hyperbolic
TD (NS)	time difference - navigation satellite
TD1, TD2 .	time difference signal output
TKE	track angle error
TMA	terminal area
T/O	takeoff
TTG	time to go

o Arabic Letter Listing (caps) - (cont'd)

V, v	velocity output of inertial platform
Vat	along track speed
V_g	ground speed
Vct	cross track speed
VFR	visual flight rules
VLF	very low frequency
VMC	visual meteorological condition
V_{MO}	maximum structurally safe operating speed
VOR	very high frequency omnidirectional radio range
VOR (H)	high altitude (jet route) VOR facility
VOR (L)	low altitude VOR facility
VOR (T)	terminal VOR facility
VREF	speed reference for slant track glideslope
WPT	waypoint
WPT1, WPT2, .	the sequence of waypoints which comprise a flight plan
VWPT	vector waypoint, a waypoint commanded by ATC which differs from the original flight plan waypoint
VWPT1, VWPT2, ..	the sequence of waypoints which comprise a revised flight plan commanded by ATC
Z_A	altitude
Z_{AC}	command altitude

o Greek Letter Listing (lower case)

α	attenuation constant
$'\alpha$	proportionality constant
βm	magnetic course to waypoint
γ	time between pulses
δ	drift angle
δt	time error
ϵa	accelerometer bias error
ϵg	gyro drift rate
$\epsilon \gamma$	deviation of actual from command glideslope on slant track
θ	bearing to a waypoint, facility, or hazard
θ	phase error
λ	wavelength of signal
ρ	slant range to a waypoint, facility, or hazard
ρ	aircarrier and military aircraft density
σ A	3σ heading error
σ AT	3σ along track error
σ CT	3σ cross track error
σ d	standard deviation of position error
σ GS	1σ glideslope error
σ h	3σ altitude error
σ LOC	1σ localizer error
σ P1, σ P2.	standard deviation of time error on each path
σ t	standard deviation of time error
σ TD1, σ TD2	standard deviation of time difference error
σ v	3σ speed error
σ	standard deviation of phase error
τA	operator anticipation time constant
τL	operator error smoothing lag time constant
τN	operator short neuromuscular delay
τT	position fixing frequency in terms of track error
τu	position fixing frequency in terms of NAVSAT
φ	relative phase between signal and error voltage
ψ	ionospheric reflection coefficient
ω	radian frequency of carrier signal

o Greek Letter Listing (caps)

Δ	an increment in an associated variable
ΔCT	an increment in crosstrack distance
ΔETA	an increment in ETA
Δf	fractional frequency deviation
Δfuel	an increment in fuel volume
ΔZ, ΔH	an increment in altitude
Δrms	rms statistic of radial DTD system
ΔTD1, TD2.	differential time difference calibration signals
ΔV	an increment in speed

APPENDIX A

EVENT SEQUENCE DIAGRAM

Appendix A contains the detailed Event Sequence Diagrams which were constructed in an effort to correlate the elements of cockpit activity related to navigation and communication with the ATC system.

Four topics are described in this set: navigation management, VFR flight, IFR flight and all-weather landing.

The diagrams show the mission oriented events taking place during the nine phases of flight: preflight, taxi, take off, climb out, departure, enroute, arrival, approach and land. The event sequence diagrams inter-relate the pilot control and monitor functions, communication activities and navigation management tasks to the ATC system.

There are four major ESDs, each of which is subdivided into the flight phases described in the preceding paragraph: (Figure A-1 shows the organization of the diagrams.)

Figure A-2	Navigation Management Event Sequence Diagram
Figure A-3	VFR Flight Plan Event Sequence Diagram
Figure A-4	IFR Flight Plan Event Sequence Diagram
Figure A-5	All-Weather Landing Event Sequence Diagram

The VFR and IFR Event diagrams specify the mission sequence from pre-flight briefing to taxi in and system shutdown. The diagrams identify the navigation management functions, communication management functions, and aircraft control and monitor tasks for each flight phase. They also indicate cognizant traffic control and surveillance units and show the surveillance technique employed, e.g., direct communication, Airfield Surveillance Detection Equipment (ASDE), interrogation, etc. The communication management events diagram ties together the traffic control and surveillance structure by showing both air-to-ground and ground-to-air communications.

The VFR and IFR event sequence diagrams define the nominal navigation management functions. The detailed form of the tasks depends upon aircraft avionics fit, control display configuration, and operational procedures adopted by the crew member. The pilot control and monitor tasks are general. Again, the specific tasks depend upon the particular vehicle evaluated. The communication tasks are also general and depend upon the level of automation in the data link. Thus, the event sequence diagrams can be utilized in the analysis of any combination of navigation, communication, aircraft control, and monitor equipments. Figure A-1 illustrates the general organization of the Event Sequence Diagrams (ESD's).

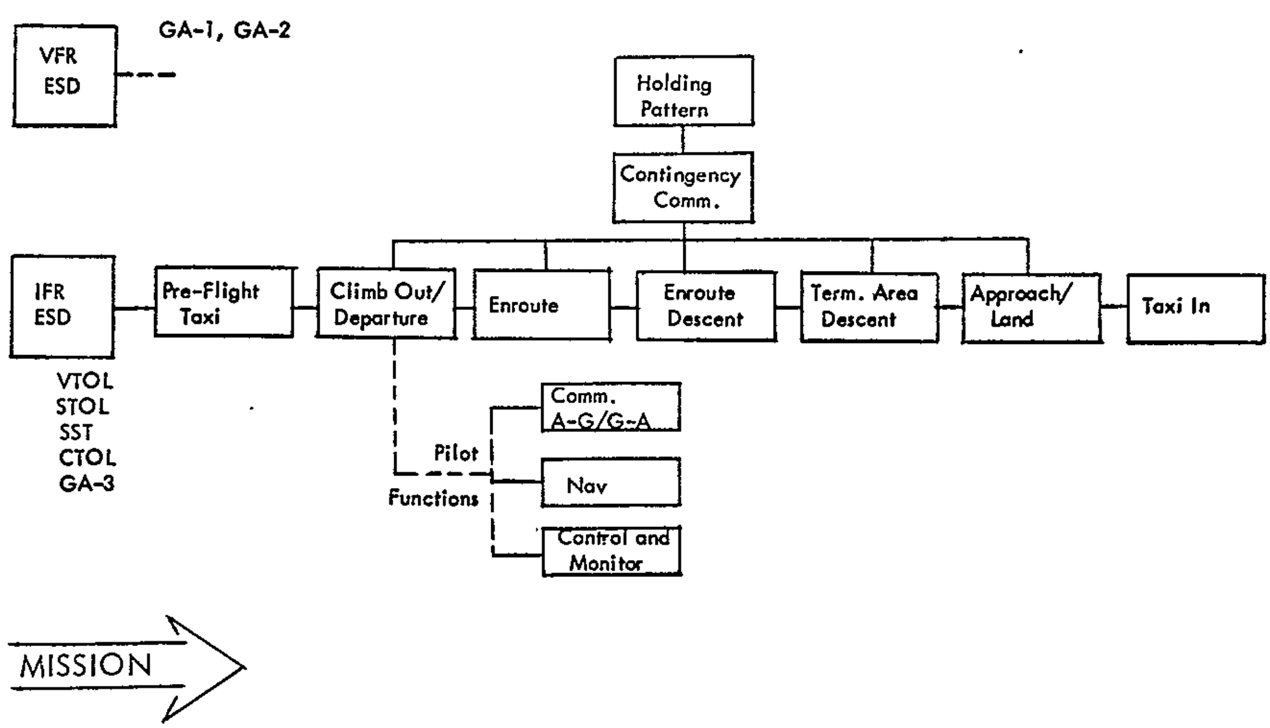


Figure A-1. Organization of the Pilot/ATC Event Sequence Diagrams

A.1 NAVIGATION MANAGEMENT EVENT SEQUENCE DIAGRAM

Figure A-2 is the first of nine navigation management event sequence diagrams. The diagrams are serial operational flow diagrams showing tasks essential to accomplishment of the navigation management function. The on-line processing functions provide data to the parallel functions of communications and aircraft control and monitor. The navigation management workload requires the pilot to:

(1) review current forecast: outputs, wind along-track component and wind cross-track component

(2) initially set up the system: initiate navigation system operation; includes switch-on, system alignment, and data insertion

(3) review current leg: confirm desired course, distance to go

(4) program next waypoint: insert data for next leg (terminal area or enroute)

(5) reprogram system - in-flight: insert revised flight plan data

(6) acquire position data: measure and evaluate position information; used to generate steering points

(7) update steering signal: compute track angle error, cross-track distance error, distance to go

(8) check flight path status: output display track angle error, cross track distance, command altitude, command speed, required time of arrival.

(9) check flight plan status: confirm Limit Logic; confirm aircraft flight path within specified limits of flight plan

(10) prepare report: assemble and store standard report data, abbreviated report data for surveillance link to ATC

The pilot or computer performs the navigation management tasks in serial fashion throughout the entire flight profile.

A.2 VFR EVENT SEQUENCE DIAGRAM

Figure A-3 presents the VFR Flight Plan Event Sequence Diagram for the GA1 and GA2 aircraft profile in which it is assumed that a single pilot performs all navigation, communication and control tasks. Aircraft profile events such as "complete turn", "climb to cruise altitude", "reach cruise altitude" relate the communication and navigation functions to the profile. The typical A-G and G-A communication functions are related to the appropriate ATC function, such as "enroute surveillance", "descent surveillance", etc. Navigation management functions are processed in parallel with the communication and control functions.

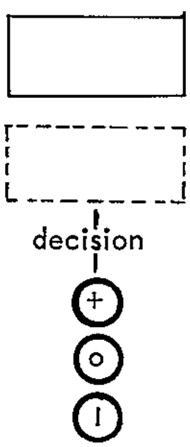
The VFR event sequence diagram illustrates that the Flight Plan Reference System and Limit Logic function can be initiated and maintained only with acquisition of surveillance data. In this flow chart, take-off, approach and landing activities are performed as present-day VFR operation without ATC cognizance.

A.3 IFR FLIGHT PLAN EVENT SEQUENCE DIAGRAM

Figure A-4 presents the complete IFR Flight Plan diagram for five classes of users; VTOL, STOL, SST, CTOL and GA3. Air-to-ground and ground-to-air communications with the specified control and surveillance units are identified. The surveillance procedure is identified for voice link, digital data link, or flight following on surveillance radar as required. The pilot performs the communication, navigation and control tasks in parallel. The timing of the tasks are keyed to aircraft events in the control channel. Throughout all flight profiles, contingency communications are allowed, for the contingency communication event may introduce the need for a modification to the navigation system set up, thus necessitating implementation by the reprogram task. The contingency communication event can be triggered by the Limit Logic if either the airborne or ground based system observes aircraft position or navigation state as "out of limits". A request by ATC for the aircraft to take up a holding pattern is triggered by the contingency communication channel.

A.4 UTILIZATION OF THE EVENT SEQUENCE DIAGRAM

The event sequence diagrams utilized in the pilot workload analysis are tied to the aircraft flight profiles documented in Section 2. The time base for the event sequence diagrams is derived from the flight profiles. These diagrams were used as the principal control tool in defining workload events which were subsequently subjected to measurement in determination of pilot loading. The following block diagram symbols and logic notation are used in the event sequence diagrams:



– a function

– an event

– the decision factor at a logic point

– "and/or gate"; follow any combination of input and output paths

– all outputs and all inputs are required

– "or gate"; follow one path only

EVENT SEQUENCE DIAGRAM

VFR FLIGHT PLAN - GA1, GA2
Phase 1 -- Pre-Flight Briefing

PRECEDING PAGE BLANK NOT FILMED.

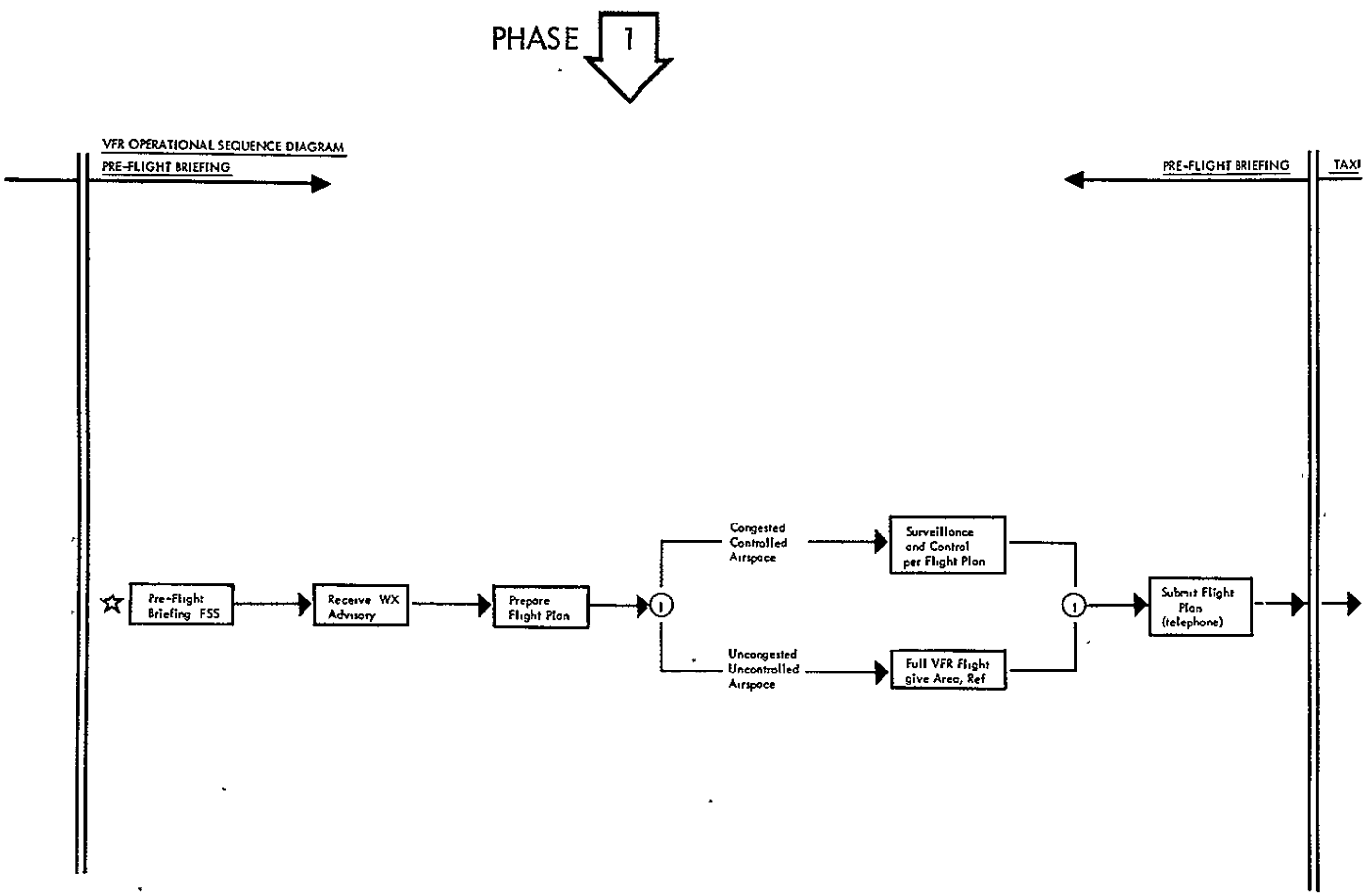


Figure A-3(a). - Phase 1.

PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM
NAVIGATION MANAGEMENT

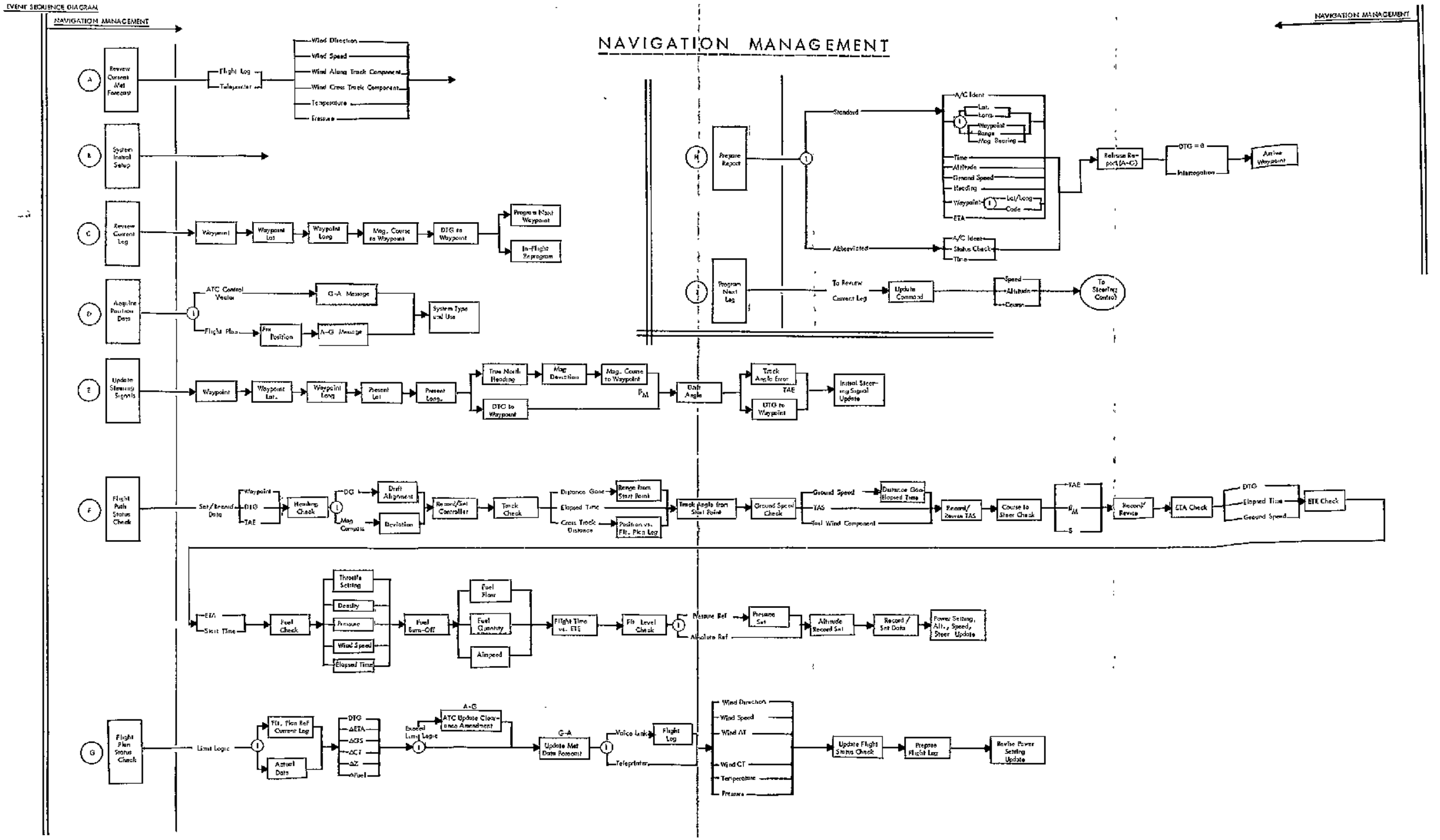


Figure A-2.

FOLDOUT FRAME 2

PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM

VFR FLIGHT PLAN - GA1, GA2
Phase 2 -- Taxi
Phase 3 -- Take-Off/Climb-Out

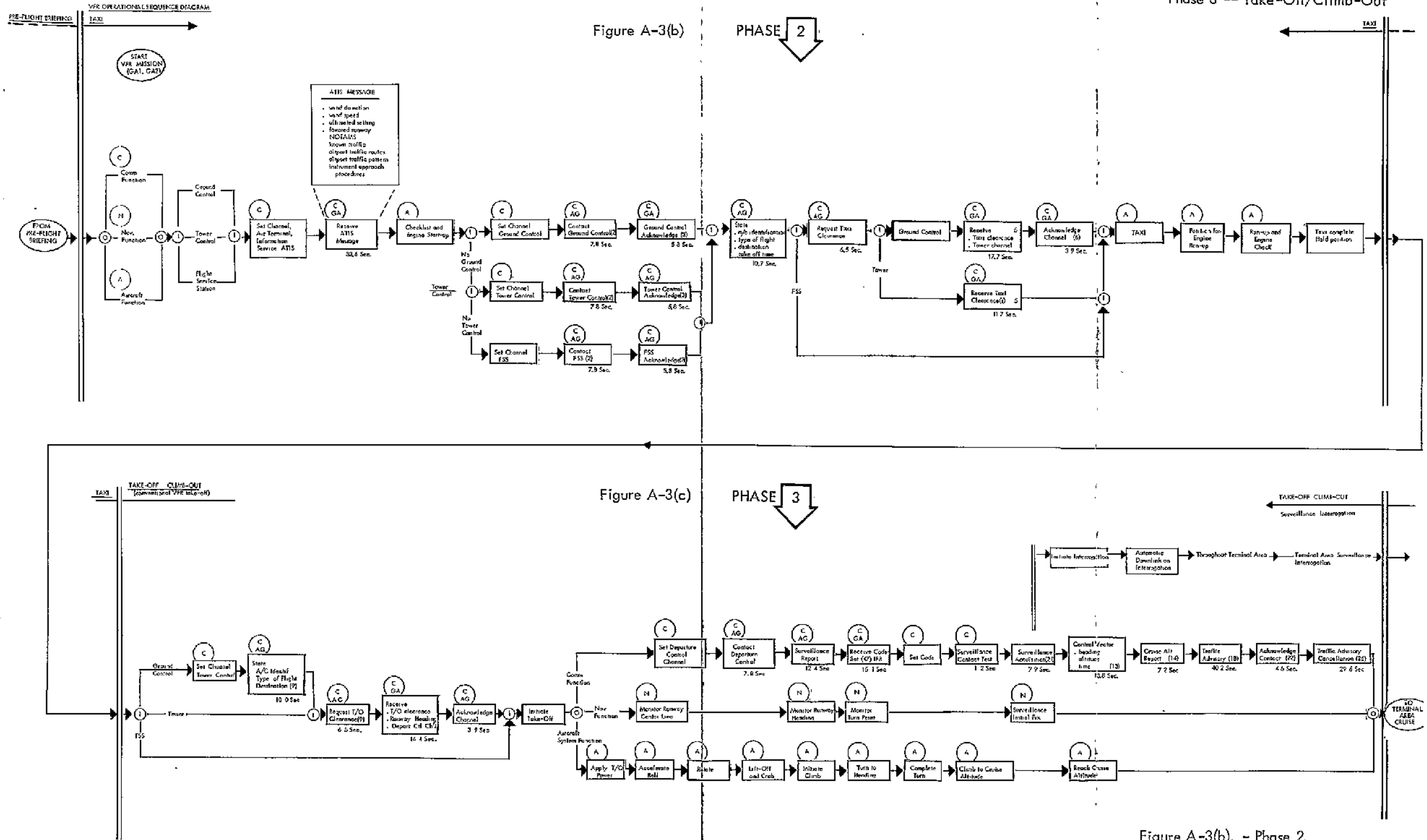


Figure A-3(b). - Phase 2.
&
Figure A-3(c). - Phase 3.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

PRECEDING PAGE BLANK NOT FILMED

EVENT SEQUENCE DIAGRAM

VFR FLIGHT PLAN

Phase 4 -- Terminal Area Cruise - Departure
Phase 5 -- Enroute Cruise
Phase 6 -- Terminal Area Cruise - Arrival

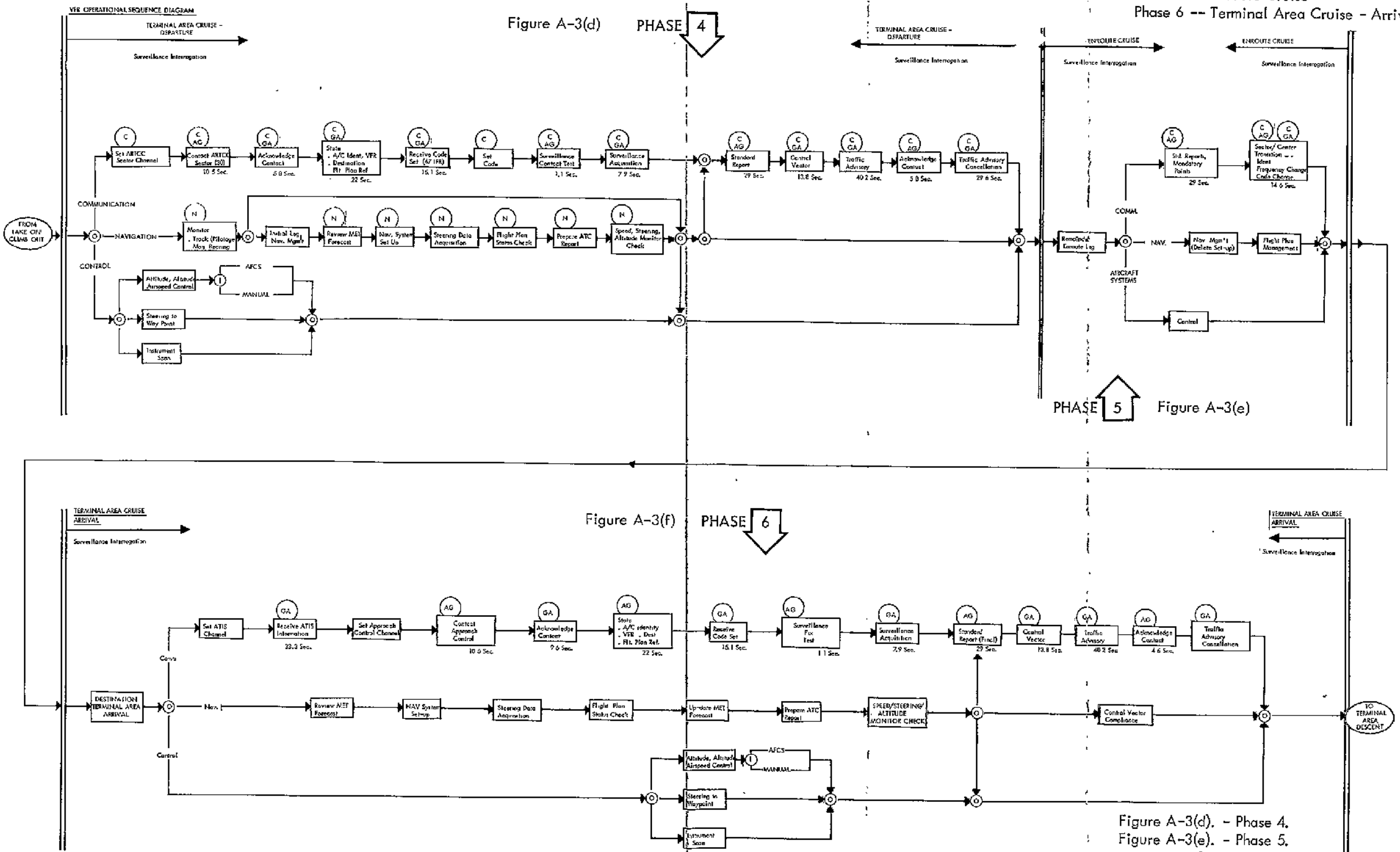


Figure A-3(d). - Phase 4.
Figure A-3(e). - Phase 5.
&
Figure A-3(f). - Phase 6.

A FOLDOUT FRAME 1

FOLDOUT FRAME 2 B

PRECEDING PAGE BLANK NOT FILMED

EVENT SEQUENCE DIAGRAM

VFR FLIGHT PLAN

Phase 7 -- Terminal Area Descent
Phase 8 -- Approach to Enter Pattern/ Final Approach
Phase 9 -- Taxi-In

Figure A-3(g) PHASE 7

Figure A-3(h) PHASE 8

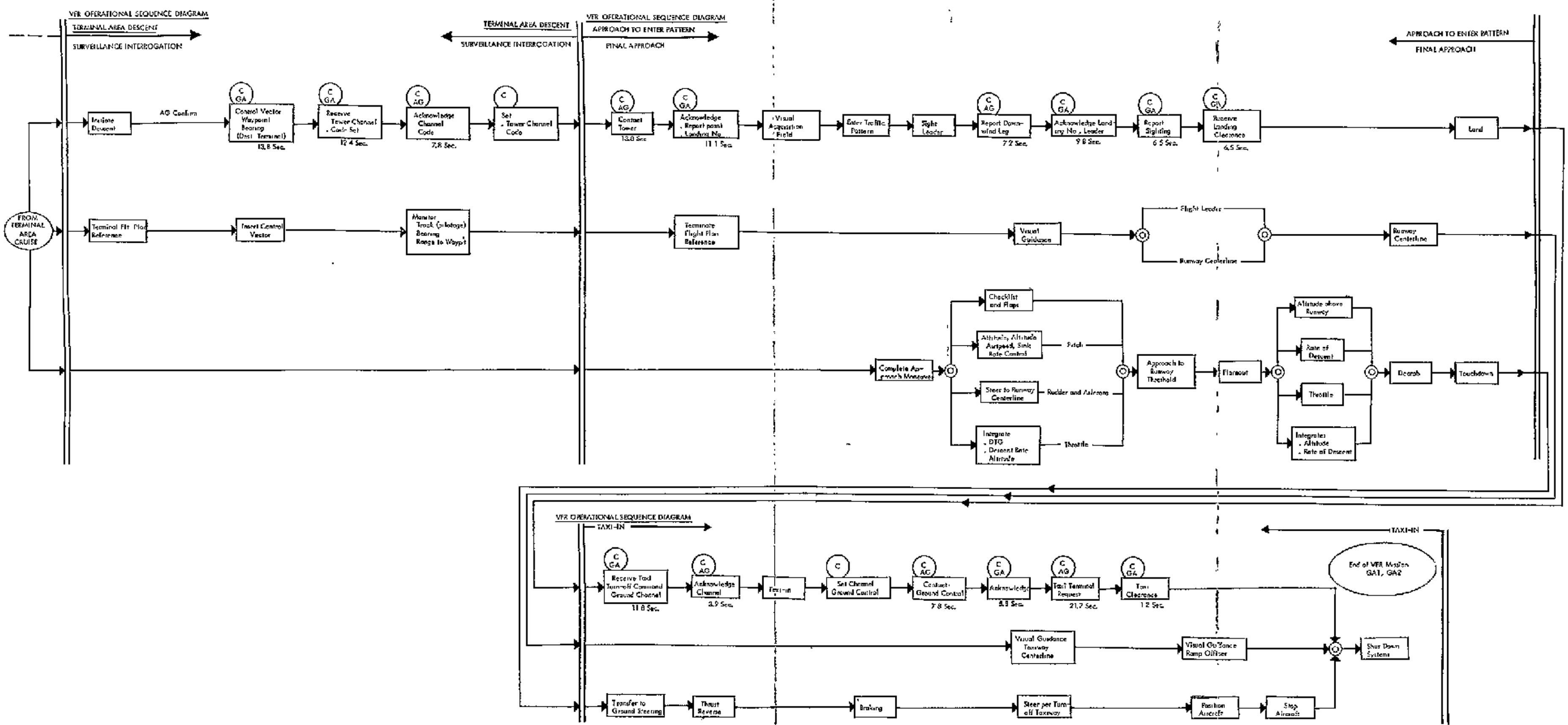


Figure A-3(i) PHASE 9

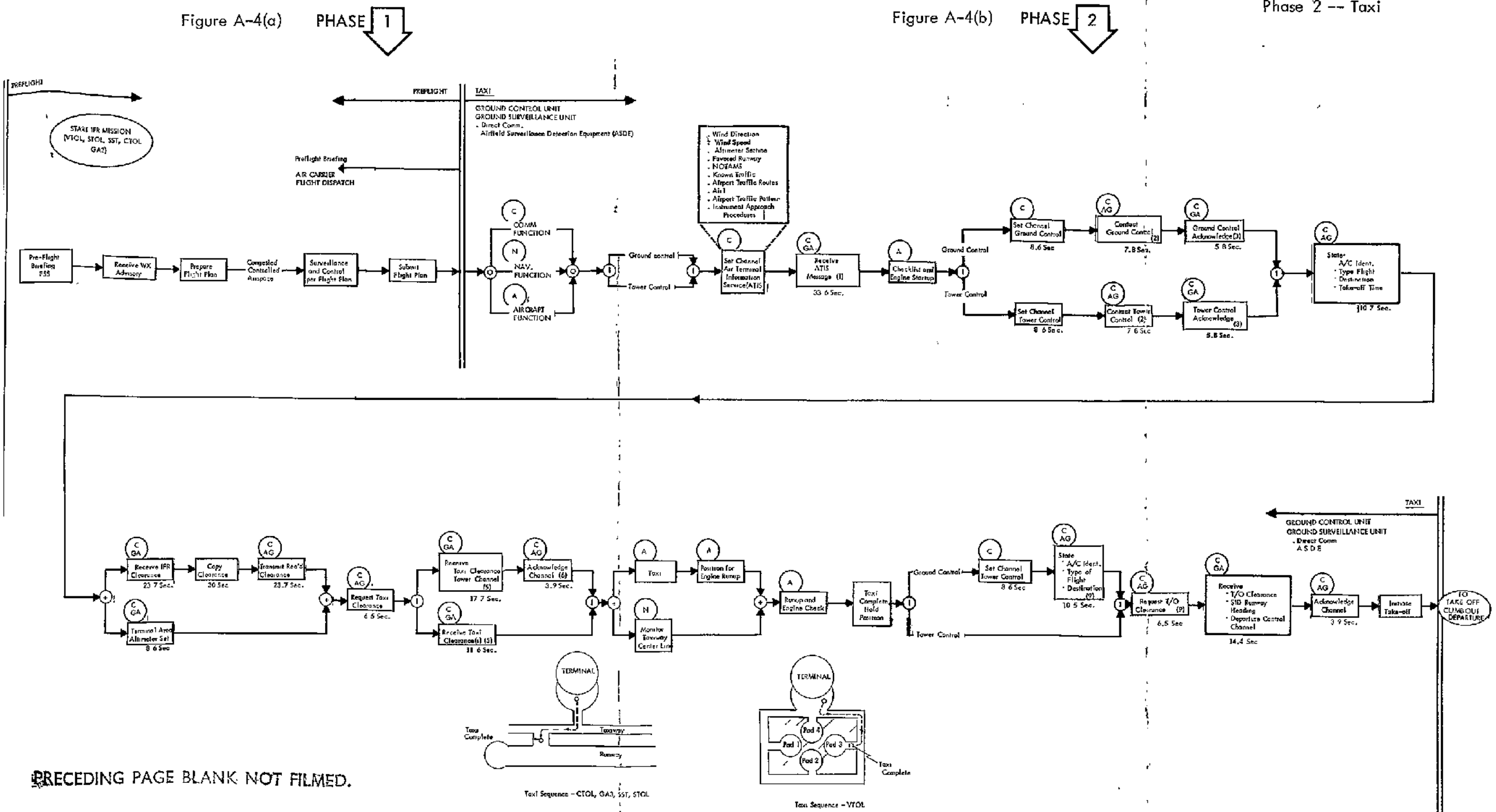
Figure A-3(g). - Phase 7.
Figure A-3(h). - Phase 8.
&
Figure A-3(i). - Phase 9.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN
Phase 1 -- Pre-Flight
Phase 2 -- Taxi



PRECEDING PAGE BLANK NOT FILMED.

Figure A-4(a). - Phase 1.
&
Figure A-4(b). - Phase 2.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

PRECEDING PAGE BLANK NOT FILMED.

PHASE 3 Figure A-4(c)

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 3 -- Take-Off/Climb-Out/Departure

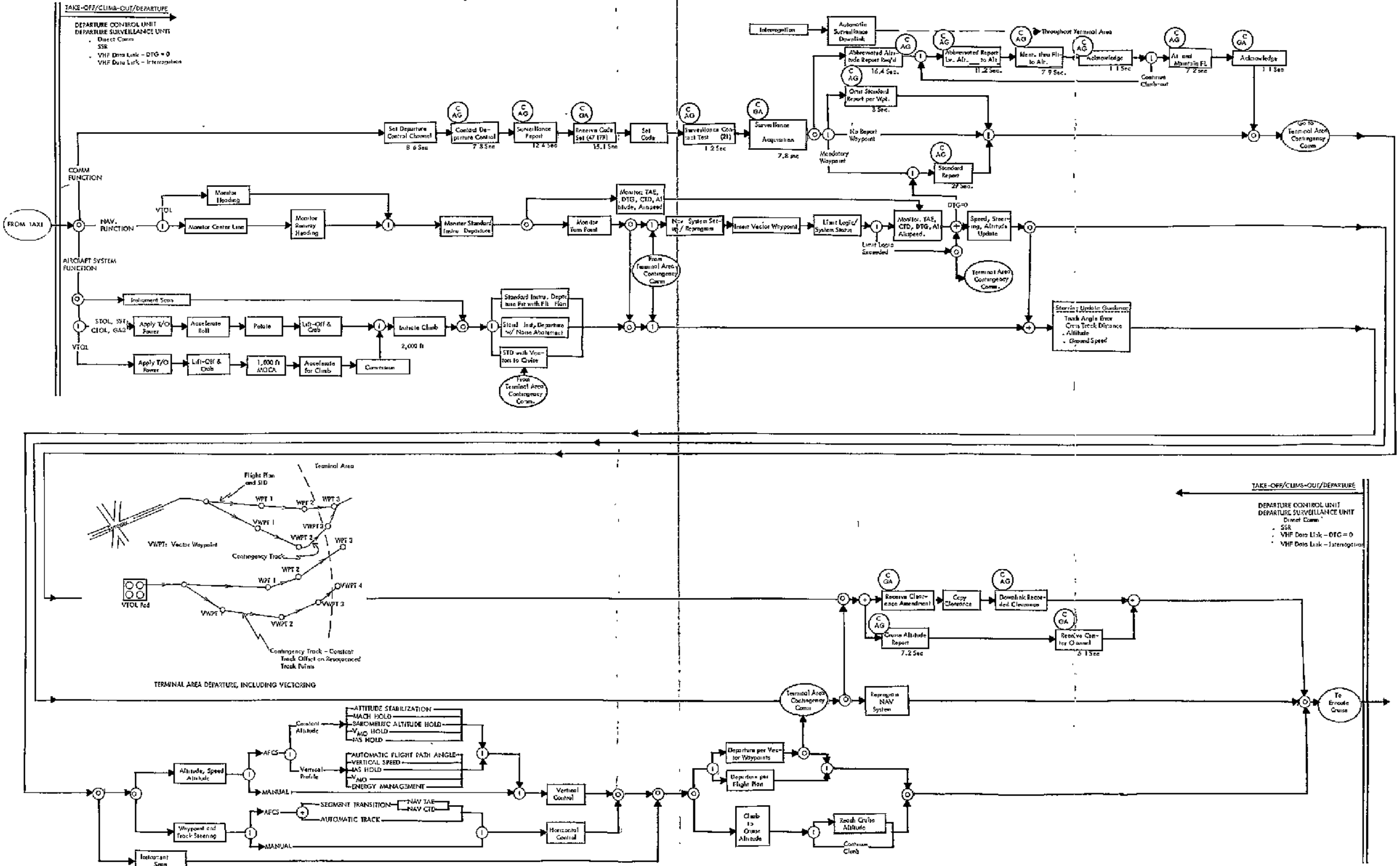


Figure A-4(c). - Phase 3.

A

FOLDOUT FRAME 1

FOLDOUT FRAME 2

PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 4 -- Enroute

PHASE 4 Figure A-4(d)

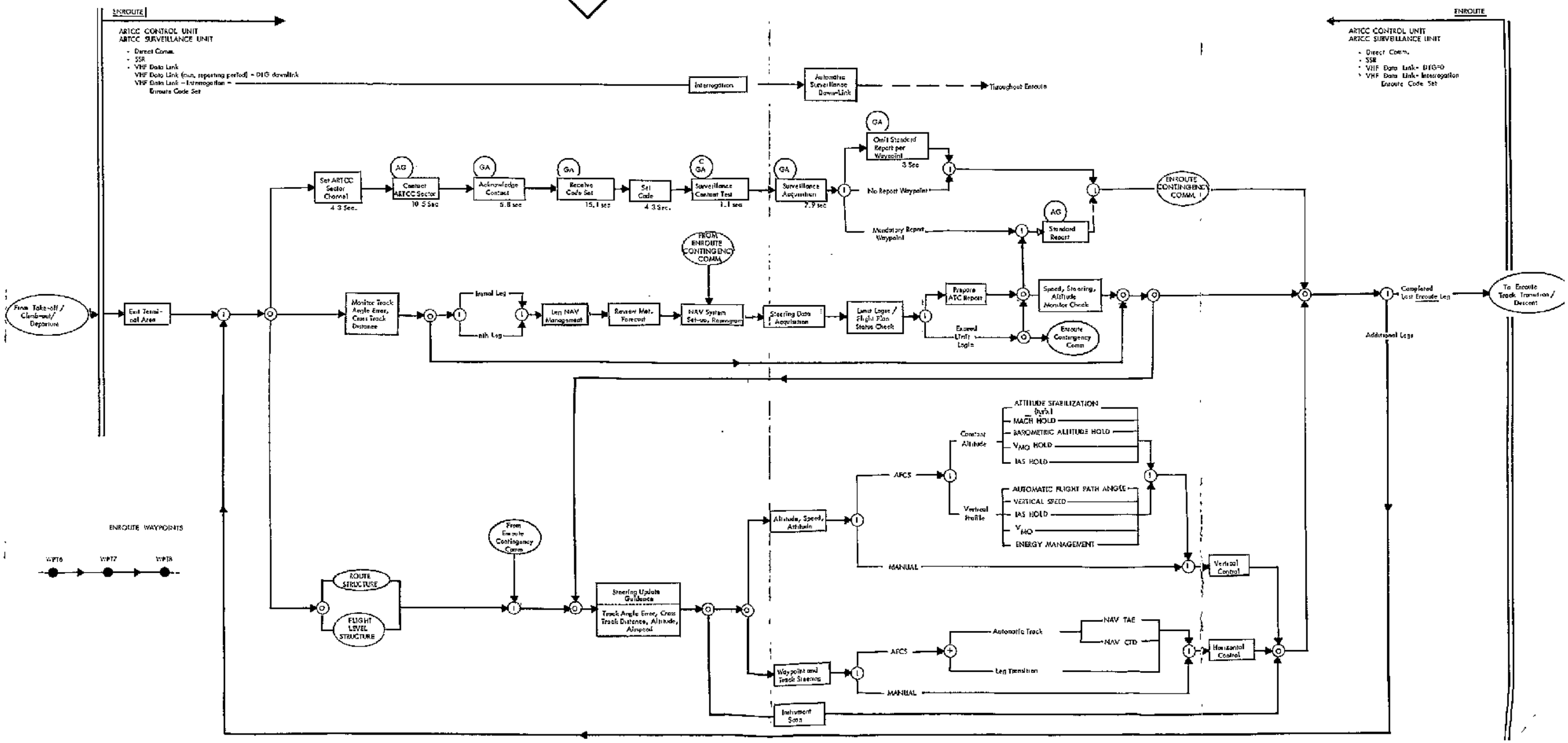


Figure A-4(d). - Phase 4.

FOLDOUT FRAME 2

PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 5 -- Enroute Descent/Track Transition

PHASE 5 Figure A-4(e)

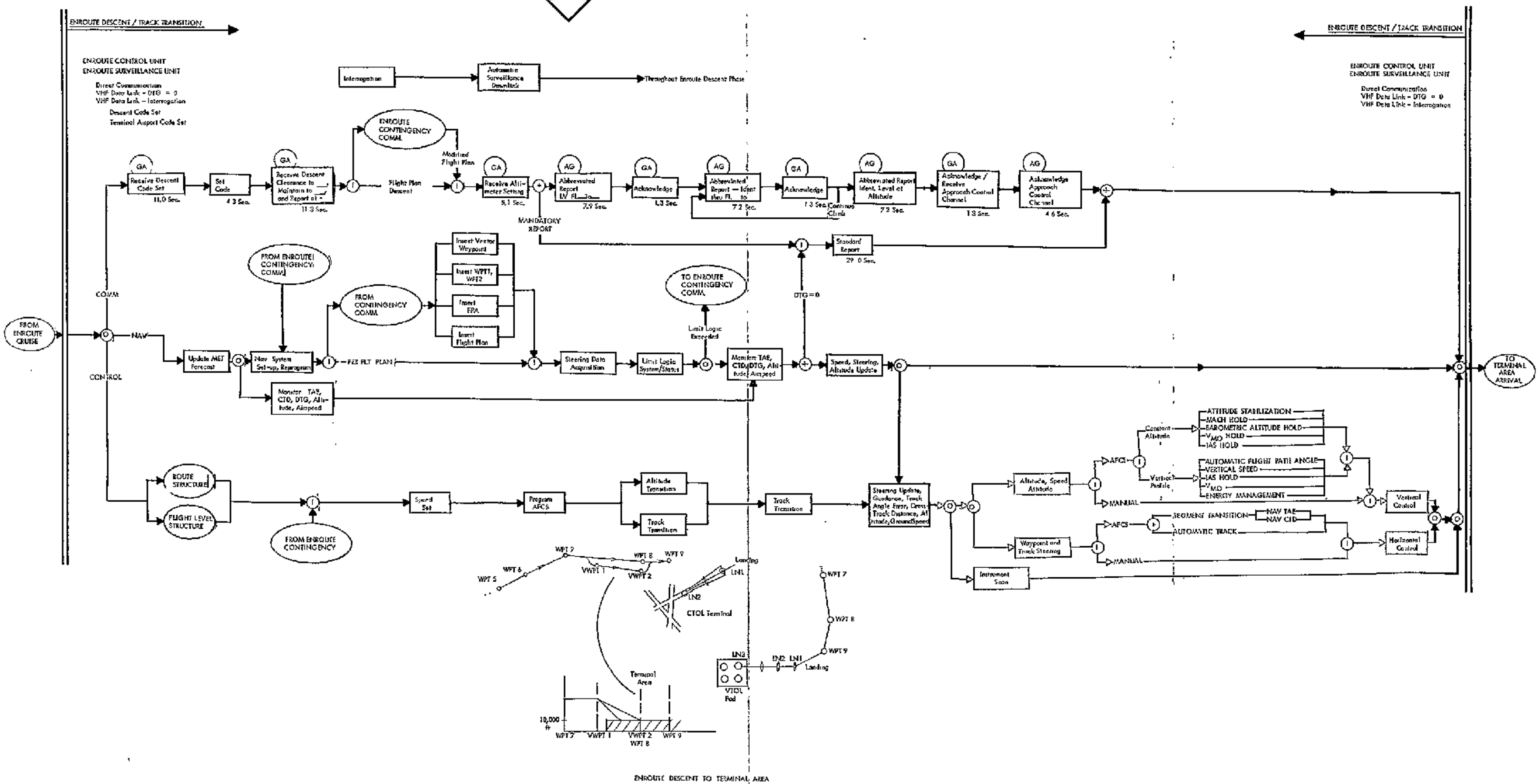
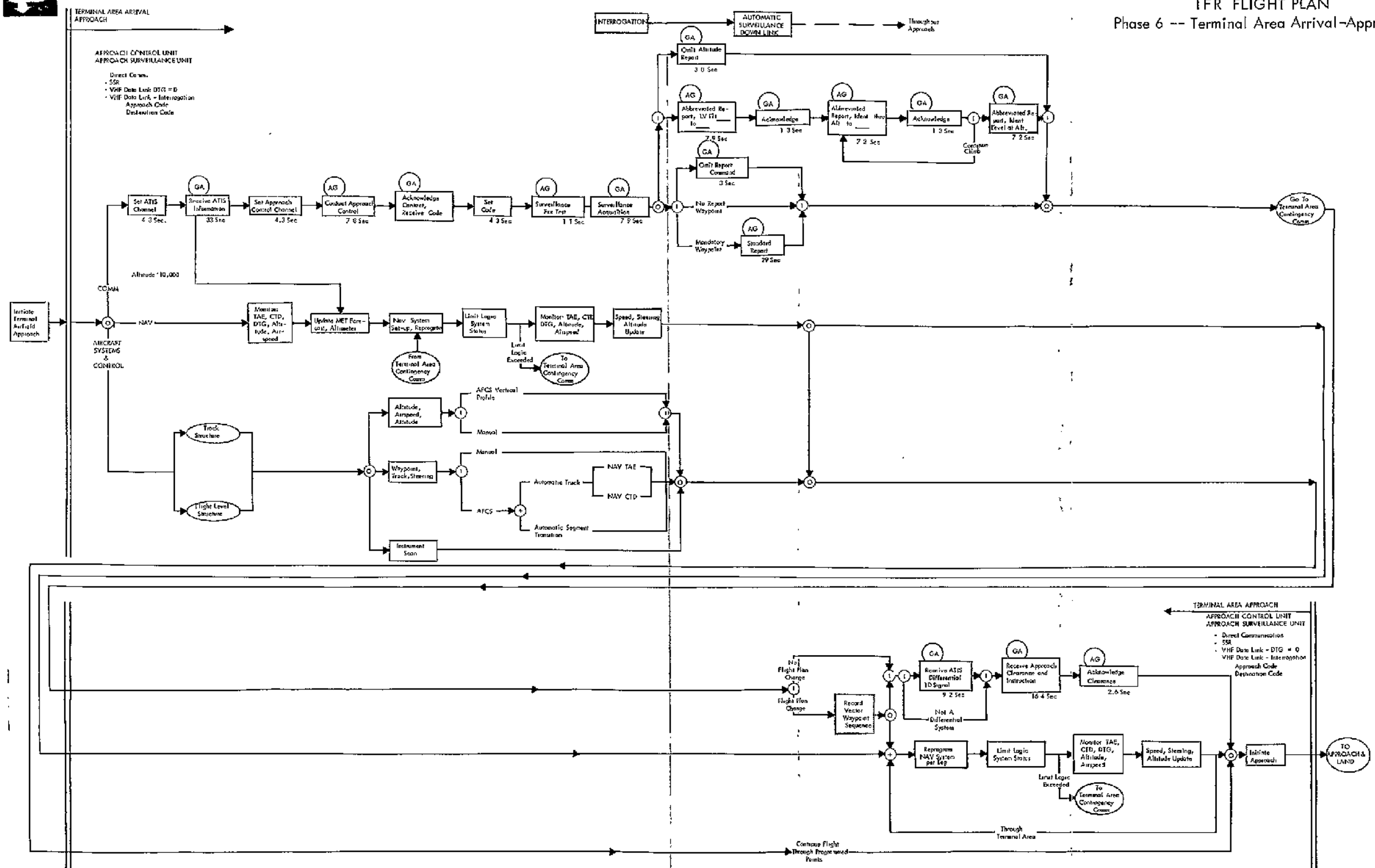


Figure A-4(e). - Phase 5.

PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM
IFR FLIGHT PLAN
Phase 6 -- Terminal Area Arrival-Approach



A FOLDOUT FRAME 1

PHASE 6 Figure A-4(f)

Figure A-4(f) - Phase 6. FOLDOUT FRAME 2 B

PRECEDING PAGE BLANK NOT FILMED

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 7a -- Approach and Land (VTOL STOL)
Phase 8a -- Taxi-In

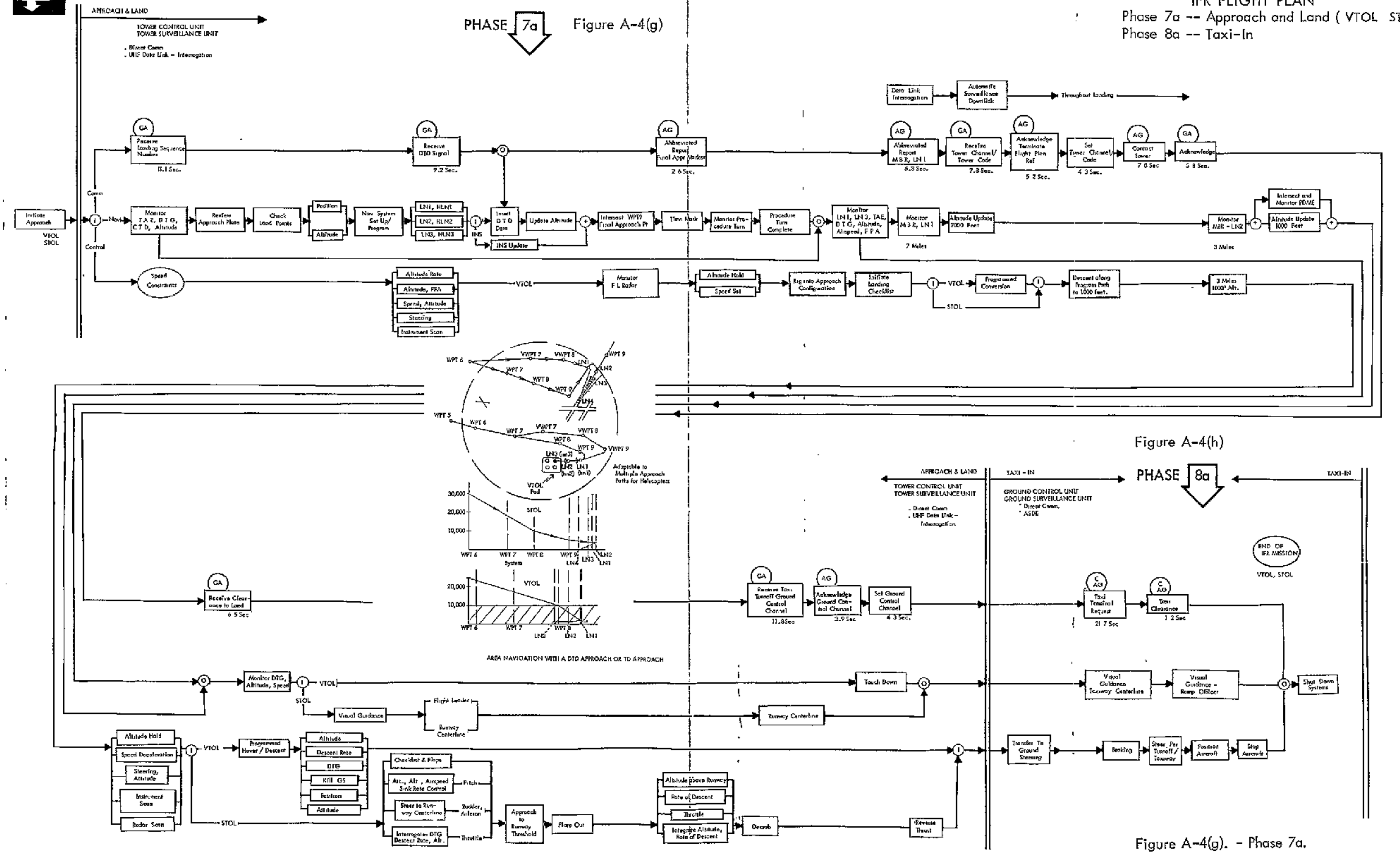


Figure A-4(g). - Phase 7a.
&
Figure A-4(h). - Phase 8a.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 7b -- Approach and Land
(SST, CTOL, STOL, GA3)

PHASE 7b Figure A-4(i)

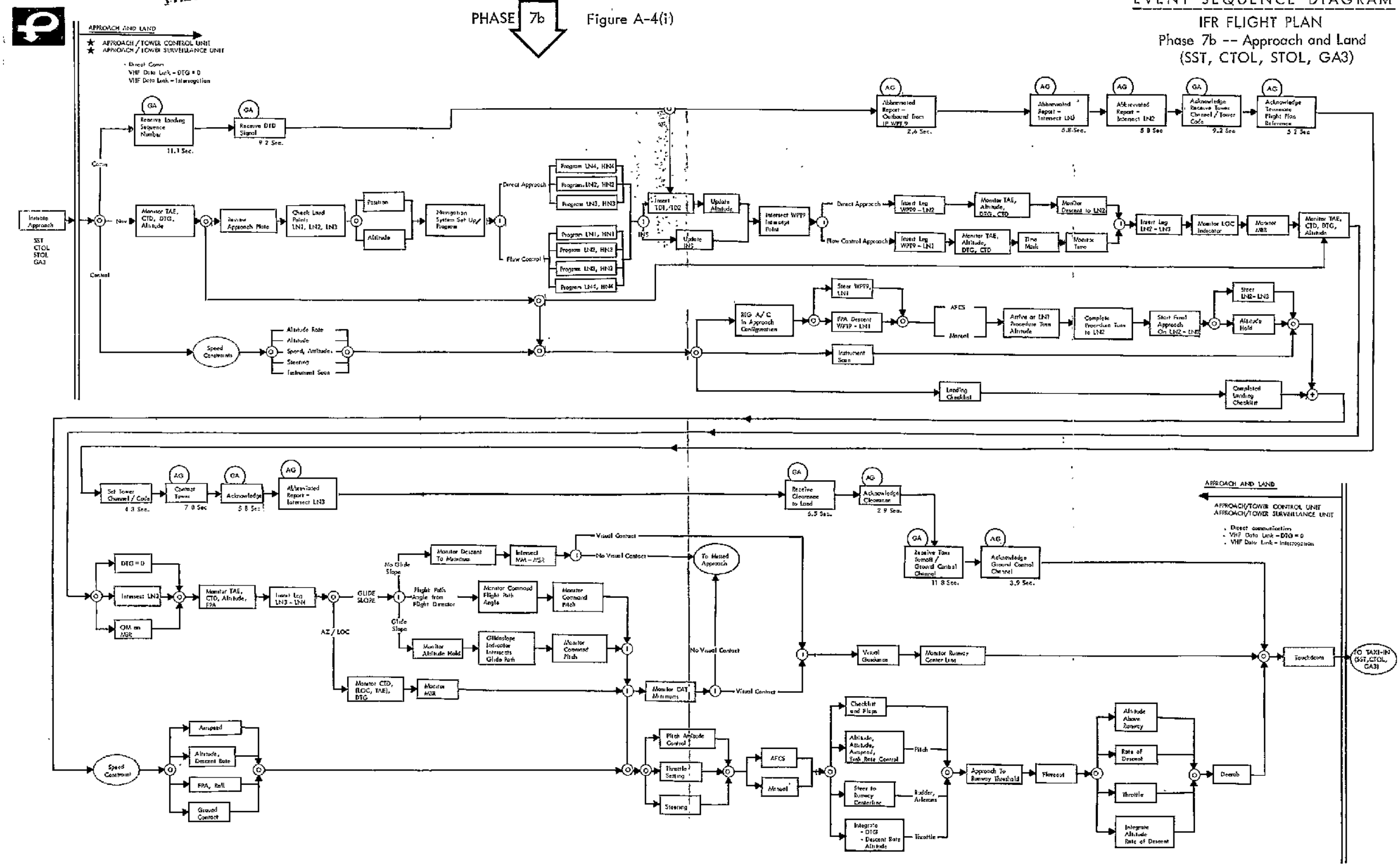
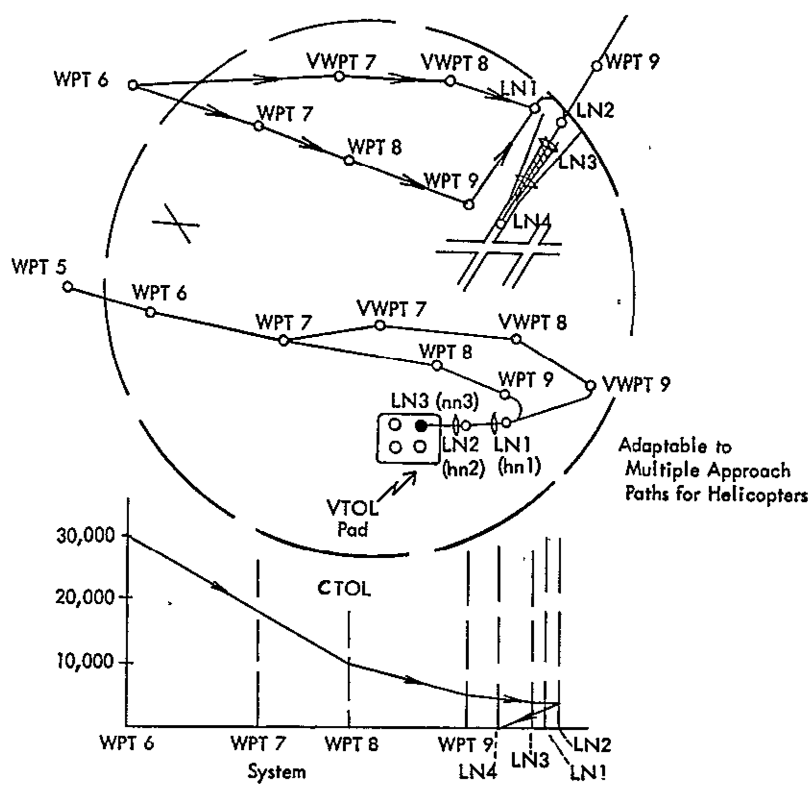


Figure A-4(i). - Phase 7b.

A FOLDOUT FRAME 1

FOLDOUT FRAME 2 B

PRECEDING PAGE BLANK NOT FILMED.



Area Navigation with a DTD Approach or a TD Approach

PRECEDING PAGE BLANK NOT FILMED.

IFR FLIGHT PLAN
Phase 8b -- Taxi-in (VTOL, STOL)
Phase 9 -- Contingency Phase --
-- Hazard Avoidance --

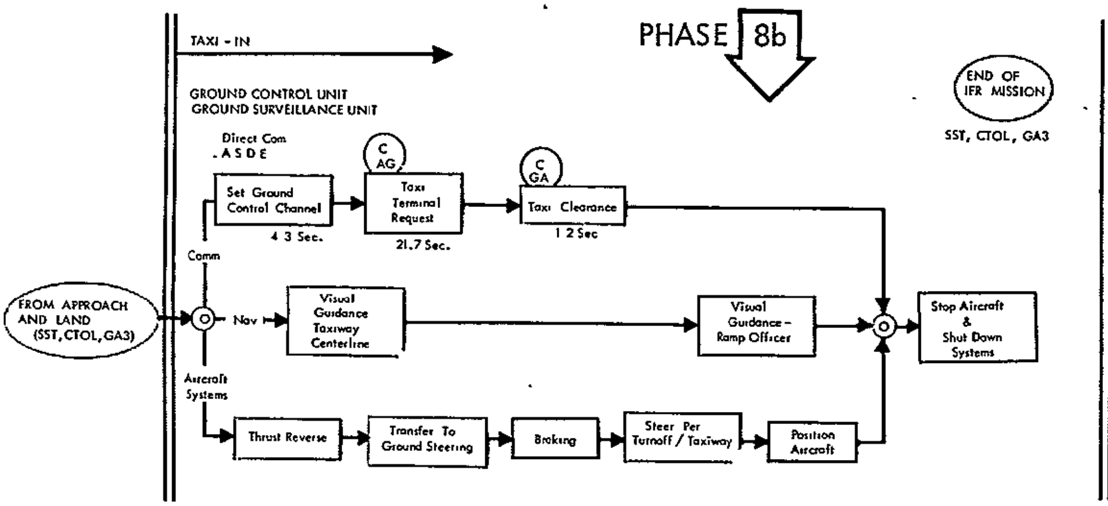


Figure A-4(j)

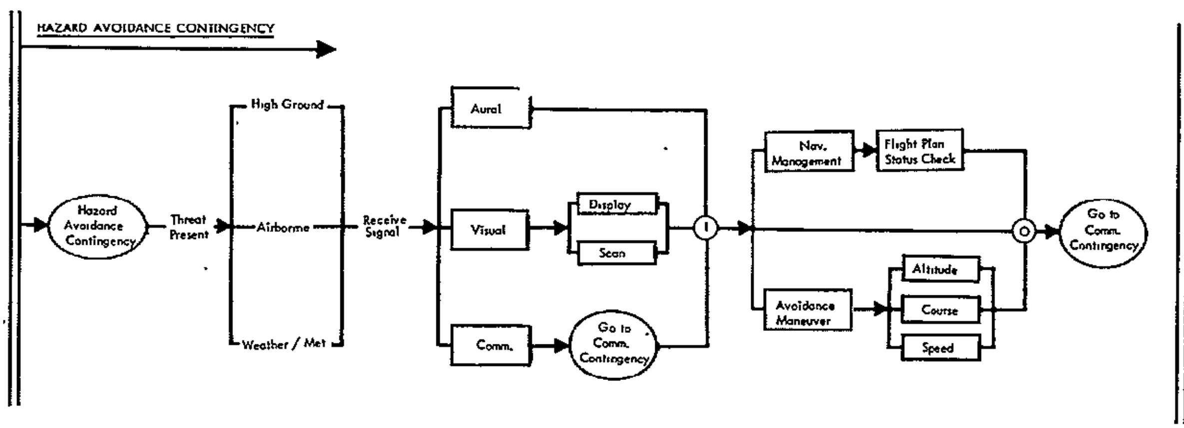


Figure A-4(k)

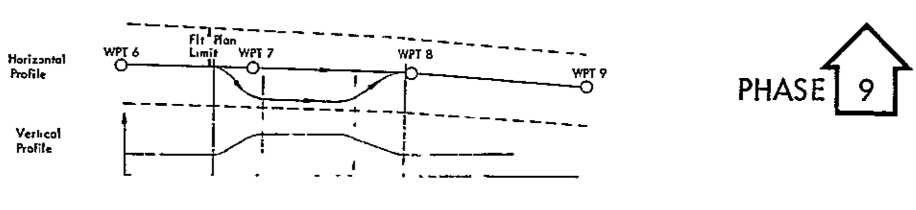
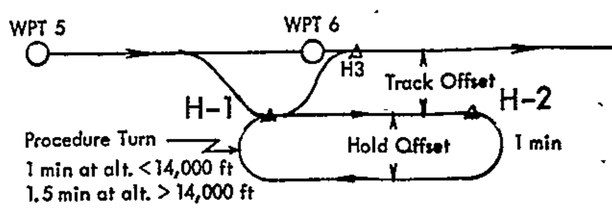


Figure A-4(j). - Phase 8b.

Figure A-4(k). - Phase 9

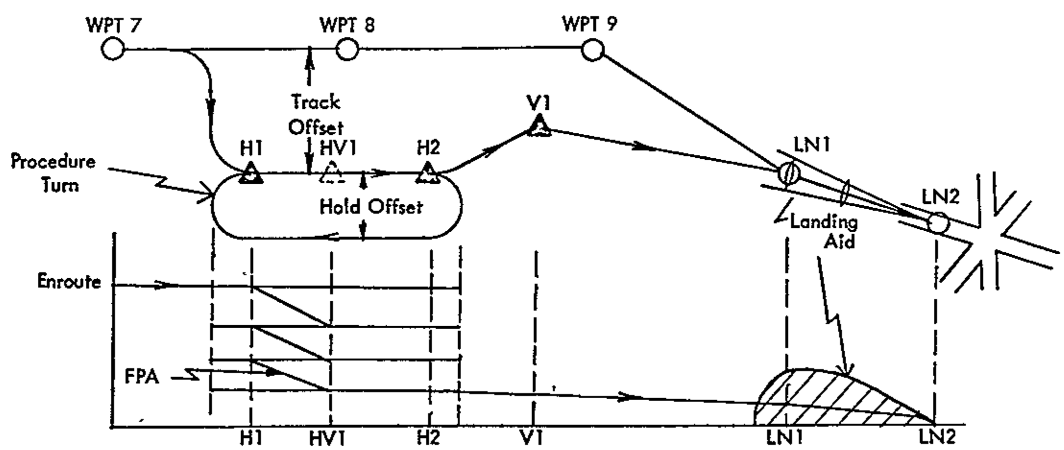


ORIGINAL FLT PLAN: WPT 5, 6, 7. . .

MOD 1 FOR AFCS: H1, H2, HOLD OFFSET

MOD 2 FOR FLT PLAN: H1, H3, WPT 7, . . .

ENROUTE OR TERMINAL AREA HOLD

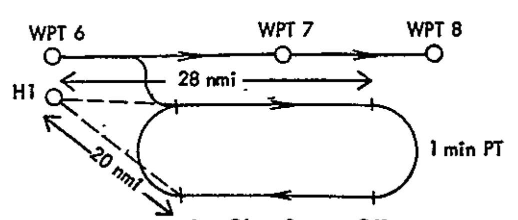


Original Flight Plan: WPT 7, WPT 8, WPT 9
Original Land: WPT 9, LN1, LN2
MOD 1 for AFCS (Horizontal): HI, H2, Hold Offset
MOD 2 for AFCS (Vertical): H1, HV1, FPA
MOD 3 for Land: H2, V1, LN1, LN2

LN1, LN2

Insert Standard Preflight
Never change
Select Destination, Select "Land"

TERMINAL AREA APPROACH HOLD



H1 is Ghost Beacon, Offset
a known distance from track
of flight plan

HOLDING PATTERN WITH DTG

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 10 -- (Contingency Phase) -- Holding Pattern --

Phase 11 -- (Contingency Phase) -- Conting. Comm. --

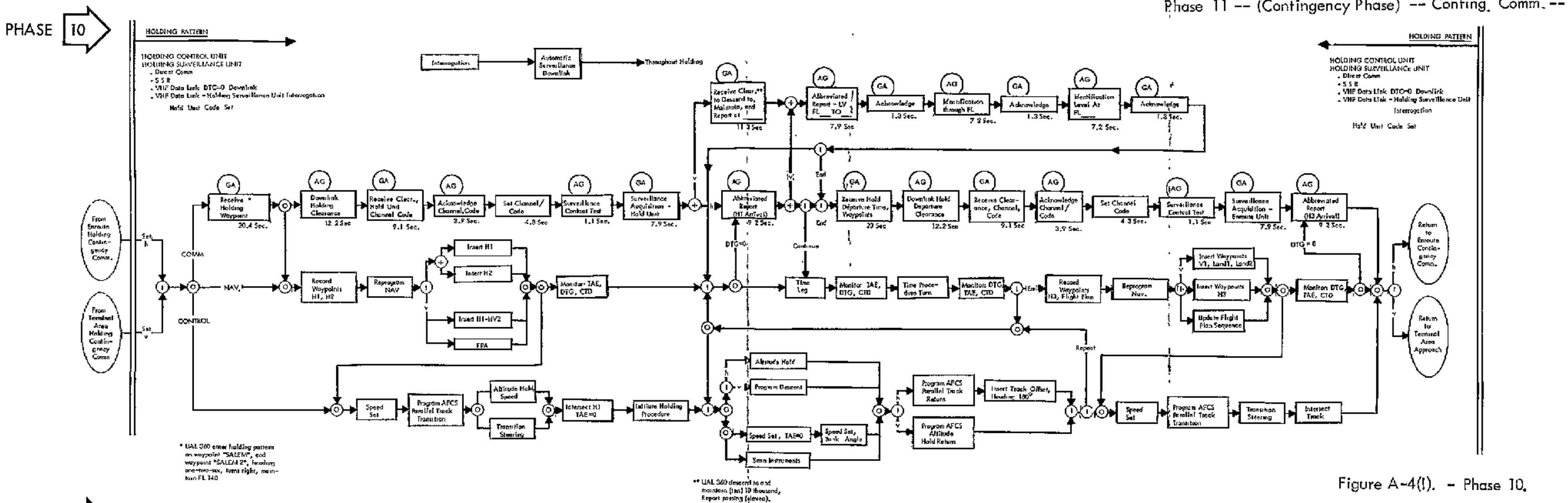
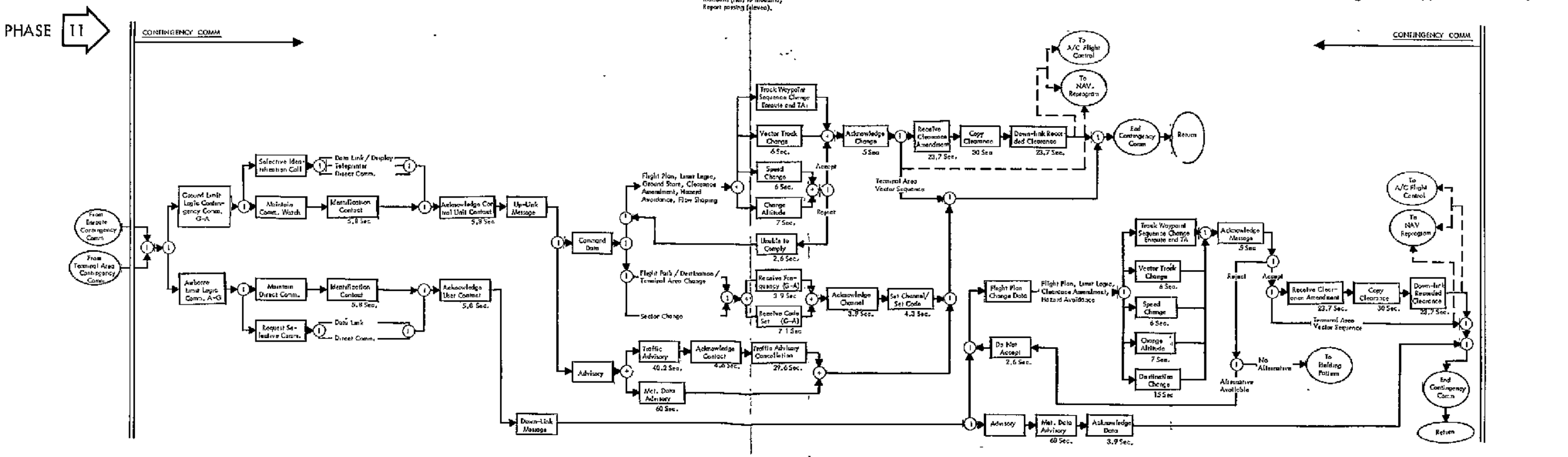


Figure A-4(l). - Phase 10.



FOLDOUT FRAME 1

Figure A-4(m). - Phase 11.

FOLDOUT FRAME 2

EVENT SEQUENCE DIAGRAM

ALL-WEATHER LANDING OPERATIONAL PROCEDURES

PRECEDING PAGE BLANK NOT FILMED.

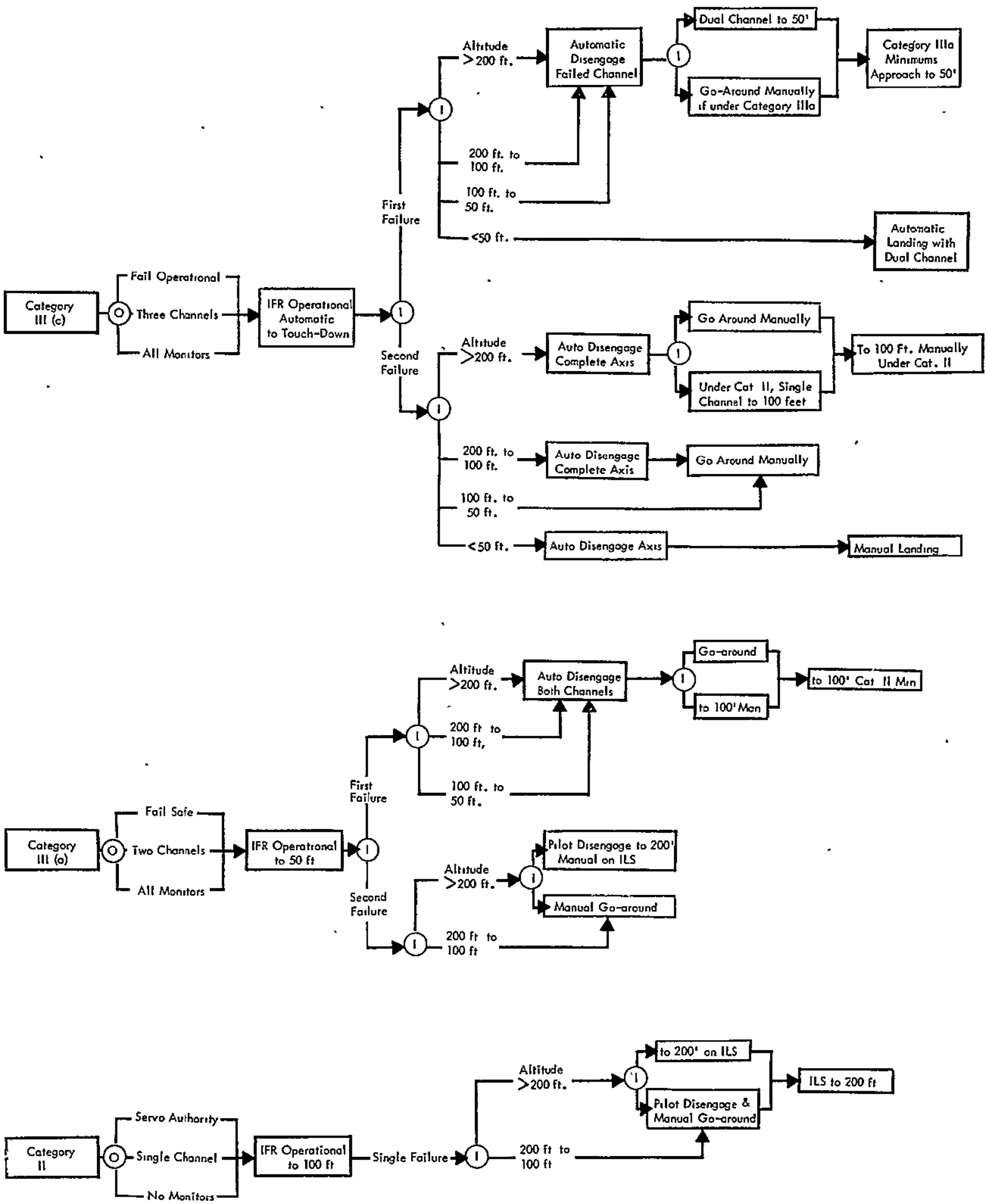


Figure A-5

APPENDIX B

COCKPIT INFORMATION NEEDS

Appendix B summarizes cockpit information needs for six classes of aircraft - VTOL, STOL, SST, CTOL, GA1, GA2 and GA3.

1. Aircraft State - Primary consideration is to know the basic elements of information which affect the aircraft's ability to take off, to cruise and to land safely. These will include at least: minimum airspeed, attitude, vertical velocity, and fuel remaining.

2. Hazard Avoidance - To safely manage the aircraft's flight path requires knowledge of: airfield runway situation, presence of high ground, presence of turbulence, location of obstacles, and proximity to other aircraft.

3. Command Information - To efficiently and economically control aircraft flight path requires knowledge of: steering error, error in expected time of arrival, relationship to command speed, start of climb and descent points, and error in vertical position and rate.

4. Situation Information - To make valid judgments regarding future action it is necessary to know: present track, speed, altitude, vertical velocity, present time, aircraft position, and any error in position.

5. Systems Status - The pilot must be able to monitor and control operational status of all subsystems of the navigation/communication/control system complex.

6. Environmental Situation - Significant flight path variables are influenced by ambient temperature, wind direction and velocity, atmospheric pressure, density altitude, and natural hazards (e.g., ice, restrictions to visibility, and turbulence).

7. Special Navigation Procedures - Air crew must have the capability to cope with a variety of special procedures involving computation, analysis and judgment (e.g. alternate routing procedures, slant tracks, point of no return, ADIZ boundaries, notices to airmen, control time maneuvers, etc.).

8. Special Operational Procedures - These include the capability to comply with special noise abatement procedures during takeoff and climb-out, sonic boom minimization criteria, and speed and noise restrictions imposed during the approach and landing phase.

9. ATC-Related Control Information - The conflict avoidance task requires information about: radius of turn, rate of closure, passenger 'g' limits, proximity to other aircraft, intentions of aircraft approaching a conflict situation, terminal situation at expected time of arrival, and path stretching and speed control capabilities.

10. Communications - Navigation/ATC Related - The primary NAV-ATC related communication capabilities of significance in the information set relate primarily to the ability to: request, receive, revise, acknowledge, and evaluate a clearance.

11. Aeronautical Data - the air crew member has a responsibility to be familiar with a wide range of aeronautical data which appear in the form of : NOTAMS, advisories, verbal instructions, and both permanent and temporary postings on maps, charts and approach charts.

The information set out in the following Tables provides an amplification of required/desired cockpit information summarized in Section 3.3. The data is related to the three major tasks of navigation, communication and control. Indication is given regarding: (1) the source of the tabulated information, (2) whether or not it is sensed, or derived by computation, or induced by the pilot, (3) whether it is reported to or by the pilot, (4) whether it is achieved manually or automatically, and (5) whether it is airborne or ground-derived (ATC).

The cockpit information needs are summarized in the following Table (B-1) To differentiate the cockpit needs of different classes of aircraft, the entries in the table are identified by the following symbols:

- x - All aircraft (VTOL, STOL, CTOL, SST, GA3, GA2, GA1) require the information
- + - SST and CTOL jet require this information
- o - VTOL, STOL, CTOL, SST and GA3 require this information; GA2 and GA1 do not
- s - SST, only, requires the information
- v - VTOL, only, requires the information
- c - CTOL, only, requires the information
- g3 - GA3, only, requires the information
- g - GA2 and GA1, only, require the information

TABLE B-1

PILOT INFORMATION NEEDS

COCKPIT INFORMATION — GROUP & COMPONENT ELEMENT	WHEN: Pre-Flight	WHEN: Taxi	WHEN: Take Off, Accelerate	WHEN: Climb, Depart	WHEN: Cruise, En Route	WHEN: Descent, Approach	WHEN: Land	WHEN: Roll Out, Taxi	WHEN: Dock	PURPOSE: AIRCRAFT NAV	PURPOSE: AIRCRAFT CTR'L	PURPOSE: AIRCRAFT MGMT.	PURPOSE: ATC SURVEILL.	PURPOSE: ATC CTR'L	PURPOSE: ATC ADVISE	IS INFO: Required NOW	IS INFO: Required FUTURE	IS INFO: Desired NOW	IS INFO: Desired FUTURE	IS INFO: Accuracy	IS INFO: Frequency of Use	INFORMATION SOURCE - USE: Aircraft Sensed or Measured	Aircraft Computed-Man	Aircraft Computed-Aid	Aircraft Displayed	Aircraft Retain in Aircraft	Ground Report to ATC	Ground Relay from ATC
1.0 AIRCRAFT STATE																												
1.1 SPEED																												
1.1.1 V_1, V_R, V_2	x		x								x					x	x						x			x		
1.1.2 V_{mmo}				x	x	x					x	x				x	x						x			x		
1.1.3 Calibrated Air Speed			x	x	x	x	x			x	x	x		x		x	x					x		g	o			x
1.1.4 True Air Speed				x	x	x				x	x			x		x	x					x			x	x	x	x
1.1.5 Mach Number				x	x	x				x	x	x		x		x	x					x			x	x	x	x
1.1.6 Min. Safe Approach Speed, V_{so} (Flare, Touch Down)							x				x												x			x		
1.1.7 Equivalent Air Speed				s	s	s						s					s							s	s	s		
1.2 ANGLE OF ATTACK			x	x	x	x	x				x						o	o	g			x			x	x		
1.3 AIRCRAFT ATTITUDE			x	x	x	x	x				x					x	x					x			x	x		
1.4 GROSS WEIGHT	x		x	x	x	x	x				x	x				x	x						x			x		
2.0 HAZARD AVOIDANCE																												
2.1 AIRFIELD SITUATION																												
2.1.1 See Taxiways, Runways, All Visibility Conditions		o	o				o	o	o	o							o	o				o			o	o		
2.1.2 See Obstacles on Runways, Taxiways, All Vis. Conditions		o	o				o	o	o	o							o	o				o			o	o		
2.1.3 Observe Runway Centerline, All Wx			o				o			o	o						o	o				o			o	o		
2.1.4 Observe Runway Threshold, All Wx							o			o	o						o	o				o			o	o		
2.2 HIGH GROUND AVOIDANCE			x	x	x	x	x				x					g	x	s				x			x	x		
2.3 WEATHER AVOIDANCE																												
2.3.1 Clear Air Turb.				x	x	x				x	x			x	x	g	x	s				x			x		x	x
2.3.2 Prop Wash, Jet Wake, Turb. Wake			x	x	x	x	x				x				x		x	x				x			x	x		x
2.3.3 Turbulence In or Near Cloud			x	x	x	x	x			x	x			x	x	x	x					x			x		x	x
2.4 AIRCRAFT AVOIDANCE																												
2.4.1 Position Warning Information			x	x	x	x	x				x		x	x		x	x					x			x			x
2.4.2 Collision Avoidance Capabilities			o	o	o	o	o				o		o	o		o	o					o		o	o			o
2.5 OBSTACLE AVOIDANCE																												
2.5.1 Observe Hazards, e.g. TV Towers				x	x	x					x		x	x		x	x					x			x	x		x
3.0 FLIGHT PATH COMMAND INFORMATION																												
3.1 COMMAND COURSE																												
3.1.1 Magnetic Course			x	x	x	x	x			x			x	x		x	x					x			x			x

TABLE B-1

PILOT INFORMATION NEEDS (cont'd)

COCKPIT INFORMATION	WHEN									PURPOSE						IS INFO						INFORMATION SOURCE - USE						
										AIRCRAFT			ATC			Re-quired		De-sired				Aircraft					Ground	
GROUP & COMPONENT ELEMENT	Pre-Flight	Taxi	Take Off, Accelerate	Climb, Depart	Cruise, En Route	Descent, Approach	Land	Roll Out, Taxi	Dock	NAV	CTR'L	MGMT.	SURVEILL.	CTR'L	ADVISE	NOW	FUTURE	NOW	FUTURE	Accuracy	Frequency of Use	Sensed or Measured	Computed-Man	Computed-Aid	Displayed	Retain in Aircraft	Report to ATC	Relay from ATC
3.1.2 True Course				x	x	x				x			x	x		x	x					x			x			x
3.1.3 Grid Course			+	+	+	+	+			+			+	+		+	+					+			+			+
3.2 COMMAND HEADING																												
3.2.1 Mag. Heading		x	x	x	x	x	x	x		x	x			x		x	x					x			x			x
3.2.2 True Heading		x	x	x	x	x	x	x		x	x			x		x	x					x			x		x	x
3.2.3 Grid Heading		+	+	+	+	+	+	+		+	+			+		+	+					+			+			+
3.3 COMMAND SPEED																												
3.3.1 Calibrated A. S.			x	x	x	x					x	x	x	x		x	x					o			x			x
3.3.2 Mach Number				o	o	o				o	o	o	o	o		o	o					o			o		o	o
3.3.3 True Air Speed				x	x	x				x	x	x	x	x		x	x					x			x			x
3.3.4 Ground Speed					x					x	x	x	x	x		x	x								x			x
3.4 COMMAND ALTITUDE																												
3.4.1 Pressure Alt.			x	x	x	x				x	x	x	x	x		x	x								x			x
3.4.2 True Altitude (Airport)		o	o	o		o	o			o	o		o	o		o	o								o		o	o
3.4.3 Flight Level				x	x	x				x	x		x	x		x	x								x		x	x
3.4.4 Vertical Velocity				x	x	x				x	x		x	x			x	x				o			x			x
3.4.5 Glide Slope						x	x			x	x					x	x					x			x	x		
3.5 COMMAND TIME																												
3.5.1 Greenwich Mean Time		x	x	x	x	x	x			x	x		x	x		x	x					o			x			x
3.5.2 Req'd Time of Arrival (Departure, Approach Threshold)		x	x	x	x	x	x			x				x			x	x				o			x			x
4.0 FLIGHT PLANNING (OR INFLIGHT REPLAN) REFERENCE INFORMATION																												
4.1 POSITION REFERENCE DATA																												
4.1.1 Flight Plan Turn Points (Waypoints)	x			x	x	x				x			x	x		x	x					From	Charts		x(nmd)		x	x
4.1.2 Start Climb/ or Start Descent Points	x		x	x	x	x				x			x	x		x	x					"	"		x(nmd)		x	x
1.1.3 Mandatory Report Points	x		x	x	x	x	x			x			x	x		x	x					"	"		x(nmd)		x	x
4.1.4 Holding Points	x			x	x	x				x			x	x		x	x					"	"		x(nmd)		x	x
4.1.5 Parallel Track	x			x	x	x				x			x	x		x	x					"	"		x(nmd)		x	x
4.1.6 Path Stretch Trk.	x				x	x				x			x	x			x	x				"	"		x(nmd)		x	x
4.1.7 Glide Path	x					x	x			x						x	x					"	"		x			
4.1.8 Localizer	x					x	x			x						x	x					"	"		x			

TABLE B-1

PILOT INFORMATION NEEDS (cont'd)

COCKPIT INFORMATION: GROUP & COMPONENT ELEMENT	WHEN: Pre-Flight	WHEN: Taxi	WHEN: Take Off, Accelerate	WHEN: Climb, Depart	WHEN: Cruise, En Route	WHEN: Descent, Approach	WHEN: Land	WHEN: Roll Out, Taxi	WHEN: Dock	PURPOSE: AIRCRAFT NAV	PURPOSE: AIRCRAFT CTR'L	PURPOSE: AIRCRAFT MGMT	PURPOSE: ATC SURVEILL.	PURPOSE: ATC CTR'L	PURPOSE: ATC ADVISE	IS INFO: Required NOW	IS INFO: Required FUTURE	IS INFO: Desired NOW	IS INFO: Desired FUTURE	IS INFO: Accuracy	IS INFO: Frequency of Use	SOURCE - USE: Aircraft Sensed or Measured	SOURCE - USE: Aircraft Computed-Man	SOURCE - USE: Aircraft Computed-Aid	SOURCE - USE: Aircraft Displayed	SOURCE - USE: Aircraft Retain in Aircraft	SOURCE - USE: Ground Report to ATC	SOURCE - USE: Ground Relay from ATC
5.0 SITUATION INFORMATION																												
5.1 AIRCRAFT TRACK																												
5.1.1 Magnetic Track			x	x	x	x	x			x	v g		x	x	g	o	x	g				o	x	v	v	v	x	
5.1.2 True Track			x	x	x	x	x			x	v		x	x		x	x					x		x	x	v	x	
5.1.3 Grid Track			+	+	+	+	+			+	v		+	+		+	+					+	+	v	+		+	
5.1.4 Steering Error			x	x	x	x	x			x	x					x	x					x		x	x	x		
5.2 AIRCRAFT HEADING																												
5.2.1 Magnetic Heading	x	x	x	x	x	x	x	x		x	x			x		x	x					x		o	x	v		
5.2.2 True Heading	x	x	x	x	x	x	x	x		x	x			x		x	x					x		x	x	g3 v		
5.2.3 Grid Heading	+	+	+	+	+	+	+	+		+	+			+		+	+					+	+	+	+	g3 s		
5.2.4 Heading Error			x	x	x	x	x			x	x			g		x	x						g	x	x	x		
5.2.5 Compass Deviation			g	x	x	x	g			x						x	x						g	+	x	x		
5.2.6 Drift Angle			x	x	x	x	x			x						x	x					o	g		x	x		
5.2.7 Mag. Variation			x	x	x	x	x			x						x	x					x			x	x		
5.3 AIRCRAFT SPEED																												
5.3.1 Indicated Air Speed			x	x	x	x	x				x					x	x					x			x	x		
5.3.2 Calibrated Air Speed			x	x	x	x	x				x					x	x					c g3 g		o	x	o	g3 c g	
5.3.3 True Air Speed				x	x	x				x	x	x	x	x		x	x					x		x	x		x	
5.3.4 Mach Number				o	o	o				o	o	o	o	o		o	o					o			o		o	
5.3.5 Ground Speed				x	x	x				x			x	x			x	x				x	g		x	g	o	
5.3.6 Error in Ground Speed				x	x	x				x			x	x			x	x						x	x		x	
5.4 AIRCRAFT ALTITUDE																												
5.4.1 Pressure Alt./ Flight Level			x	x	x	x	x			x	x	x	x	x		x	x					x			x		x	g
5.4.2 True Altitude		x	x	x		x	x			x	x		x	x		x	x					x			x		x	g
5.4.3 Radar Altitude			o	o		o	o			o					o	o	o					o			o	o		
5.4.4 Error in Altitude			x	x	x	x	x			x	x	x	x	x		x	x						x		x	o	o	
5.4.5 Vertical Velocity			x	x	x	x	x			x	x		x	x		x	x					x			x		x	
5.4.6 Error in Vertical Velocity			o	o	o	o	o			o			o	o			o	o						o	o	v	o	
5.5 TIME																												
5.5.1 Greenwich Mean Time	x	x	x	x	x	x	x			x			x	x		o	x	s	g			x			x		x	
5.5.2 Estimated Time Arrival (Depart)		x	x	x	x	x	x			x			x	x		x	x							x	x		x	
5.5.3 Required Time Arrival (Depart.)		x	x	x	x	x	x			x			x	x			x	x							x			

TABLE B-1
PILOT INFORMATION NEEDS (cont'd)

COCKPIT INFORMATION — GROUP & COMPONENT ELEMENT	WHEN: Pre-Flight	WHEN: Taxi	WHEN: Take Off, Accelerate	WHEN: Climb, Depart	WHEN: Cruise, En Route	WHEN: Descent, Approach	WHEN: Land	WHEN: Roll Out, Taxi	WHEN: Dock	PURPOSE: AIRCRAFT NAV	PURPOSE: AIRCRAFT CTR'L	PURPOSE: AIRCRAFT MGMT.	PURPOSE: ATC SURVEILL.	PURPOSE: ATC CTR'L	PURPOSE: ATC ADVISE	IS INFO: Re-quired NOW	IS INFO: Re-quired FUTURE	IS INFO: De-sired NOW	IS INFO: De-sired FUTURE	Accu-racy	Fre-quency of Use	SOURCE - USE: Aircraft: Sensed or Measured	Aircraft: Computed-Man	Aircraft: Computed-Aid	Aircraft: Displayed	Aircraft: Retain in Aircraft	Ground: Report to ATC	Ground: Relay from ATC
5.5.4 Actual Time Arrival (Depart)			x	x	x	x	x			x			x	x		o	x	g						x	x		x	
5.5.5 Est. Time En Route (Time to Go)			x	x	x	x	x			x						o	x	g						x	x		x	
5.5.6 Error in ETA			x	x	x	x	x			x						o	x	g						x	x		x	
5.7 AIRCRAFT POSITION																												
5.7.1 Latitue/Longitude	o	o	o	o	o	o	o	o		o			o	o								o		o	o		o	
5.7.2 Range/Bearing (W/R Facility)			x	x	x	x	x	x		x			x	x		o	x	g				x		x	x		x	
5.7.3 Cross-Track Error (Distance to Go)			x	x	x	x	x	x		x			x	s			g	g						x	x		x	
5.7.4 Error in Position			x	x	x	x	x			x							x	g						x	x	x		
5.7.5 Error in Position on Glide Slope						x	x			x						x	x					x			x	x		
5.7.6 Error in Postion on Localizer						x	x			x						x	x					x			x	x		
5.8 FUEL SITUATION																												
5.8.1 Fuel Remaining	x	x	x	x	x	x	x	x		x	x	x				x	x					x			x		x	
5.8.2 Fuel Flow			x	x	x	x	x			x	x	x				o	x	g				x			x	x		
5.8.3 Fuel Required	x	x	x	x	x	x	x			x	x	x				o	x	g						x	x	g	o	
6.0 NAV/COM SYSTEMS STATUS																												
6.1 DIRECTIONAL REF																												
6.1.1 Comp. Deviation				x	x	x	x			x						x	x						g		x	x		
6.1.2 Magnetic Variation	g	x	x	x	x	x	x	x		x	v					x	x					x	g		x	x		
6.1.3 Grivation			+	+	+	+	+			+														+	+	+		
6.1.4 Gyro Error			+	+	+	+	+				+					+	+					+		+	+	+		
6.1.5 Gyro Precession				+	+	+	+			+						+	+						+	+	+	+		
6.1.6 Repeater Error	x	x	x	x	x	x	x	x		x						x	x						x		x	x		
6.1.7 Power Sit. (Off, Standby, On, etc.)	x	x	x	x	x	x	x	x	x	x	x					x	x					x			x	x		
6.1.8 Malf. Indic.		x	x	x	x	x	x	x	x	x	x					x	x					x			x	x		
6.2 SPEED REF																												
6.2.1 IAS = CAS Calibration			x	x	x	x	x			x	x					x	x							x	x	x		
6.2.2 CAS = TAS Clibration				x	x	x				x	s					x	x							x	x	x		
6.2.3 TAS Instrument Error				x	x	x				x						x	x						x		x	x		
6.2.4 Mach Meter Instr. Error				x	x	x				x	x					x	x						x		x	x		
6.2.5 Ground Speed Bias				x	x	x				x						+	x	+					g	o	x	x		
6.3 POSITION MEAS. SUBSYSTEM																												
6.3.1 Freq/Channel Identification		x	x	x	x	x	x	x		x						x	x							x	x			

TABLE B-1

PILOT INFORMATION NEEDS (cont'd)

COCKPIT INFORMATION	WHEN									PURPOSE						IS INFC								INFORMATION SOURCE - USE						
										AIRCRAFT			ATC			Re-quired		De-sired		Accu-racy		Fre-quency of Use		Aircraft					Ground	
GROUP & COMPONENT ELEMENT	Pre-Flight	Taxi	Take Off, Accelerate	Climb, Depart	Cruise, En Route	Descent, Approach	Land	Roll Out, Taxi	Dock	NAV	CTR'L	MGMT.	SURVEILL.	CTR'L	ADVISE	NOW	FUTURE	NOW	FUTURE					Sensed or Measured	Computed-Man	Computed-Aid	Displayed	Retain in Aircraft	Report to ATC	Relay from ATC
6.3.2 RF Correc. Factors (Sky Wave, Slant Rqr., etc.)		x	x	x	x	x	x	x		x					x	x										x	x	x		
6.3.3 Power Sit. (Off, Stdby., On, etc.)	x	x	x	x	x	x	x	x		x					x	x											x	x		
6.3.4 Malfunction Indication	x	x	x	x	x	x	x	x		x					x	x											x	x		
6.4 DEAD RECKONING SYSTEM																														
6.4.1 Velocity Bias			x	x	x	x	x			x					x	x										x	x	x		
6.4.2 Power Sit.	x	x	x	x	x	x	x	x	x	x					x	x											x	x		
6.4.3 Malfunction Indication	x	x	x	x	x	x	x	x	x	x					x	x											x	x		
6.5 AUTOPILOT NAV STATUS																														
6.5.1 Power Sit. (On, Stdby., Off, etc.)	x	x	x	x	x	x	x	x	x		x				x	x											x	x		
6.5.2 A. P./Nav. Sys. Tie-In			x	x	x	x	x			x	x				x	x											x	x		
6.5.3 A. P./ILS Tie-In						x	x	x		x	x				x	x											x	x		
6.5.4 Malfunction Indication	x	x	x	x	x	x	x	x		x	x				x	x											x	x		
7.0 ENVIRONMENTAL SITUATION																														
7.1 TEMPERATURE																														
7.1.1 Outside Air Temperature		x	x	x	x	x	x			x	x	x				x	x							x			x	g	o	
7.1.2 Temp. Gradient				o	o	o				o		o					o	o						o		o	o	o		
7.1.3 Ram Air Temp.				o	o	o				o	o	o				o	o							o			o	o		
7.1.4 Forecast Temp./Chart	x	x	x	x	x	x	x			x	x	x				x	x							x			x	x		
7.2 DENSITY ALTITUDE		o	o		o						o	o					o	o						o	o		o	o		
7.3 UPPER AIR CHART																														
7.3.1 Pressure D-Value				o	o	o				o		o				o	o								o		o		o	
7.3.2 D-Value Grad.				o	o	o				o		o					o	o								o	o	o		
7.4 WIND																														
7.4.1 Forecast Air/ Velocity	x	x	x	x	x	x	x			x	x	x				x	x							x			x	x		
7.4.2 Meas. Air/ Velocity		x	x	x	x	x	x			x	x	x				x	x							x			x		x	
7.4.3 Wind Gradient				x	x	x				x		x					x	x								x	x	x		
7.5 TURBULENCE																														
7.5.1 Turbulence in Cloud	x		x	x	x	x	x			x	x				x	x	x							x			x			
7.5.2 CAT	x		x	x	x	x	x			x	x				x	x	x							x			x			
8.0 NAVIGATION PROCEDURES																														
8.1 ALTERNATE AIRFIELDS	x				x	x	x			x					x	x	x							x			x		x	x
8.2 PARALLEL TRACKS	x			x	x	x				x			x	x		x	x							x			x		x	x

TABLE B-1
PILOT INFORMATION NEEDS (cont'd)

COCKPIT INFORMATION	WHEN									PURPOSE						IS INFO								INFORMATION SOURCE - USE						
										AIRCRAFT			ATC			Re-quired		De-sired		Accu-racy		Fre-quency of Use		Aircraft					Ground	
GROUP & COMPONENT ELEMENT	Pre-Flight	Taxi	Take Off, Accelerate	Climb, Depart	Cruise, En Route	Descent, Approach	Land	Roll Out, Taxi	Dock	NAV	CTR'L	MGMT.	SURVEILL.	CTR'L	ADVISE	NOW	FUTURE	NOW	FUTURE					Sensed or Measured	Computed-Man	Computed-Aid	Displayed	Retain in Aircraft	Report to ATC	Relay from ATC
8.3 AIRWAYS	x			x	x	x				x			x	x		x	x							x			x		x	x
8.4 GREAT CIRCLE TRACKS	o			o	o	o				o			o	o		o	o							o			o		o	o
8.5 SLANT TRACKS	x		x	x	x	x				x			x	x			o	x	g					x			x		x	x
8.6 CONTROL TIME MAN																														
8.6.1 Path Stretching	x		x	x	x	x				x			x	x			o	x	g					x			x		x	x
8.6.2 G/ Speed Control			x	x	x	x				x			x	x			o	x	g							x	x		x	x
8.6.3 Holding Pattern					x	x				x			x	x		x	x							x			x		x	x
8.7 NAV/SYS PERF. VALIDATION																														
8.7.1 Fixing Proced.	x	x	x	x	x	x	x			x						x	x							v	x	x	x	x		
8.7.2 Air Data Sys.			x	x	x	x	x			x						x	x								g	x	x	x		
8.7.3 Velocity Sensor			x	x	x	x	x			x						x	x								g	x	x	x		
8.7. 4 Time Check	x	x	x	x	x	x	x			x							x	x						x		g	x	x		
8.7.5 Directional Ref.				x	x	x	x			x						x	x							x	s	x	x	x		
8.7.6 DPS Perf. Check	x			x	x	x				x						o	o	g	g					x	o	x	x	x		
9.8 CHART PROCEDURES																														
8.8.1 Moving Map Display	x		x	x	x	x	x	x		x							o	o	g					x		x	x	x		
8.8.2 Pilotage	x			x	x	x				x						x	x							x	x		x	x		
8.8.3 En route/Radio	x			x	x	x				x						x	x							x	x		x	x		
8.8.' Terminal Area	x	x	x	x		x	x	x		x						x	x							x	x		x	x		
8.8.5 pproach Charts	x	x	x	x		x	x			x						x	x							x	x		x	x		
8.8.6 Upper Air Charts	o			o	o	o	o			o						o	o							o	o		o	o		
9.0 SPECIAL PROCEDURES																														
9.1 NOISE ABATEMENT																														
9.1.1 Take Off & Accelerate Phase			x							x	x		x	x		x	x							o	g		x	x		
9.1.2 Sonic Boom				s	s	s				s	s		s	s	s		s	s						s			s	s		
9.1.3 Use of Special Climb Proced.			x	x		x				x	x		x	x		x	x							o	g		x	x		
9.1.4 Landing Phase						x	x			x	x		x	x		x	x							x			x	x		
10.0 COMMUNICATIONS																														
10.1 CLEARANCE INFORMATION																														
10.1.1 Request	x	x	x	x	x	x	x	x		x			x	x		x	x								g	x	x	s	o	g
10.1.2 Receive		x	x	x	x	x	x	x		x			x	x		x	x								g	o	x	g	g	o
10.1.3 Acknowledge		x	x	x	x	x	x	x		x			x	x		x	x										x		x	x

TABLE B-1

PILOT INFORMATION NEEDS (cont'd)

COCKPIT INFORMATION — GROUP & COMPONENT ELEMENT	WHEN: Pre-Flight	Taxi	Take Off, Accelerate	Climb, Depart	Cruise, En Route	Descent, Approach	Land	Roll Out, Taxi	Dock	PURPOSE — AIRCRAFT: NAV	CTR'L	MGMT.	ATC: SURVEILL.	CTR'L	ADVISE	IS INFO — Required: NOW	FUTURE	Desired: NOW	FUTURE	Accuracy		Frequency of Use		INFORMATION SOURCE - USE — Aircraft: Sensed or Measured	Computed-Man	Computed-Aid	Displayed	Retain in Aircraft	Ground: Report to ATC	Relay from ATC
10.1.4 Evaluate Effect on Fuel, ETA/RTÀ, ETE, Altitude Cap.		x	x	x	x	x	x			x			x	x		x	x								x	x	x	x	x	
10.1.5 Insert into Nav. Sys., Check Correctness	x	x	x	x	x	x	x			x			x	x			o	x	g							x	x	x		
10.2 FLIGHT PLAN STORE AND RETRIEVE		x	x	x	x	x	x			x	x		x	x			o	o	g							x	x	o	x	x
10.3 TACTICAL MODS TO FLIGHT PLAN																														
10.3.1 System Rec. & Displays Rqst. to Go Over, Go Around, Speed up, Change Altitude, etc.		x	x	x	x	x	x	x		x			x	x		o	o	x	g					o	g	x	o		g	x
10.3.2 Sys. Acknow.		x	x	x	x	x	x	x		x			x	x			x	x								x	x		x	
10.4 SYSTEM REPORTING CAPABILITY																														
10.4.1 Position, Time		x	x	x	x	x	x	x		x			x	x		x	x	x								x	x		x	
10.5 STANDARD VOICE CAP.		x	x	x	x	x	x	x		x			x	x	x	x	x							x	x				x	x
11.0 AERONAUTICAL DATA																														
11.1 NOTAMS	x							x		x	x	x																o		
11.2 REGULATIONS																														
11.2.1 FARs 61, 91, 123, 135	x							x		x																				
11.2.2 ICAO CA I - 5																														
11.2.3 US 101 - 113, 201 - 254, 301 - 304, 401 - 412																														
11.3 ADVISORIES	x							x		x	x	x																x		
11.4 ENROUTE & TERMINAL NAV AIDS	x									x	x																			
11.5 AIRFIELD DATA	x					x	x			x	x																	x		
11.5.1 Runway Conditions	x					x	x			x	x																	x		
11.5.2 Radio & Appr. Fac., Freq.	x					x	x			x	x																	x		
11.6 AIRCRAFT & ENGINE LOG	x								x	x	x																	x		
12.0 ATC-RELATED CONTROL INFORMATION																														
12.1 AIR-AIR CONFLICT PREDICTION																														
12.1.1 Rate of Closure Between Vehicles			x	x	x	x	x			x				x	x	x	x							x		x	x		x	x
12.1.2 Radius of Turn				x	x	x				x			x	x	x		x	x								x		x		
12.1.3 Proximity to Other Vehicles PWI or CAS			x	x	x	x	x			x			x	x	x		x	x						x		x	x		x	x
12.1.4 Other Vehicle Intention (Extrapolation of Vel. Vector)			x	x	x	x	x			x			x	x			x	x						x		x	x		x	x
12.1.5 Haz. Weather			x	x	x	x	x			x			x			x	x	x						x			x	x		x
12.2 AIR-GROUND CONFLICT PREDICTION																														

TABLE B-1
PILOT INFORMATION NEEDS (cont'd)

COCKPIT INFORMATION — GROUP & COMPONENT ELEMENT	WHEN: Pre-Flight	WHEN: Taxi	WHEN: Take Off, Accelerate	WHEN: Climb, Depart	WHEN: Cruise, En Route	WHEN: Descent, Approach	WHEN: Land	WHEN: Roll Out, Taxi	WHEN: Dock	PURPOSE AIRCRAFT: NAV	PURPOSE AIRCRAFT: CTR'L	PURPOSE AIRCRAFT: MGMT.	PURPOSE ATC: SURVEILL.	PURPOSE ATC: CTR'L	PURPOSE ATC: ADVISE	IS INFO Re-quired: NOW	IS INFO Re-quired: FUTURE	IS INFO De-sired: NOW	IS INFO De-sired: FUTURE	Accu-racy	Fre-quency of Use	SOURCE-USE Aircraft: Sensed or Measured	Aircraft: Computed-Man	Aircraft: Computed-Aid	Aircraft: Displayed	Aircraft: Retain In Aircraft	Ground: Report to ATC	Ground: Relay from ATC
12.2.1 Detect High Ground			x	x	x	x	x			x			x	x			x	x				x		x	x	x		x
12.2.2 Detect Obstacles in Flight Plan			x	x	x	x	x			x			x	x			x	x				x		x	x	x		x
12.3 TACTICAL SITUATION																												
12.3.1 Terminal Sit. for Planned ETA			x	x	x	x				x			x	x	x		x	x							x			x
12.3.2 Any Special Factors Inhibiting Movement Enroute			x	x	x	x				x			x	x	x		x	x							x			x
12.3.3 Rerouting &/or Speed Control, Path Stretching, Holding & Sequencing Roms.			x	x	x	x				x			x	x	x		x	x							x			x

APPENDIX C

NAVIGATION AND COMMUNICATIONS REQUIREMENTS

This Appendix presents a summary of the methodology used in computing the 1975 to 1985 navigation/traffic control system requirements. The results, the navigation and communication requirements, are reviewed in Volume II, Sections 3.5 and 3.6 respectively.

Traffic activity forecasts were also used to compute navigation and communication requirements. Aviation activity for selected ATC Sector and Center areas is described in Table C-I in terms of two categories of users, one called general aviation and a second called air carrier and military. The traffic for each of the selected categories was tabulated in terms of peak-minute activity. The values listed were obtained from a preliminary report provided by the Technical Monitor. The major concern was to determine the min/max range of peak traffic to be anticipated for 1985 (as shown in Table C-II).

C.1 TRAFFIC ACTIVITY FORECAST

The traffic activity forecast for 1985 at six arbitrarily selected ATC centers is presented in Tables C-I and C-II. The peak-minute densities are tabulated for each 100 square miles of a typical sector within the selected center. For example, the typical sector in the Salt Lake Center is expected to service 0.313 general aviation aircraft per minute per 100 square miles in 1985, and 0.085 air carrier and military vehicles. When the total number of sectors within the Salt Lake Center is multiplied by 1/100th of the average total area/sector, 17,300 nmi, times the peak minute GA traffic, 0.313 aircraft/100 nmi, the result shows that 1,139 GA aircraft are expected under Center Surveillance during peak-minute activity. Similarly, a peak-minute air carrier and military aircraft traffic load of 307 aircraft per minute is calculated. This process is then repeated for each of the six Centers. The results, tabulated in Table C-II, indicate a potential peak-minute min/max GA aircraft load of 1,139 to 8,544 vehicles. The range for military and air carrier vehicles is 303-457.

Table C-III presents a summary of peak hour operations at three major terminal areas taken from an FAA forecast (57). Overflights, arrivals and departures have been combined in the illustration.

Three factors significant to this study are noted:

(1) Air carriers are forecast to continue to use predominantly IFR clearances. The ratio of VFR to IFR operations will be of the order of 1/10.

(2) In contrast, General Aviation will continue to rely upon VFR flight rules to facilitate their movements. The ratio of VFR to IFR operations is forecast to be 8/1 to 10/1.

(3) The traffic congestion problems of the New York TMA, circa 1968, will be duplicated in Detroit by 1980. The present Detroit situation will be duplicated in Cincinnati by 1980.

The U.S. has twenty-two centers of air transportation activity which generate 1% or more of the nation's scheduled air carrier domestic service. These centers or communities, termed Large Hubs, sustain many airports of widely different characteristics. The airports are classified as follows:

Type Code	Definition
AC	Air carrier
GA	General Aviation
R	General Aviation airport which relieves traffic congestion at an air carrier airport
P	Airport identified as potential candidate for air traffic control services or navaids
(T)	Airport with ATC tower

TABLE C-I

TYPICAL CENTER – 1985 TRAFFIC ACTIVITY FORECAST

Typical Center	Typical Sector Type (GA: Low Med High)	Av Sector Area sq miles	# of 100 sq. mi. Units	Peak Minute General Aviation Traffic	Peak Minute Air Carrier & Military Traffic	Peak Minute GA under Center Surveillance	Peak Minute Air Carrier & Military under Center Surveillance
Salt Lake Center	Low GA High Altitude Through	17,300	173	0 313	0 085	1139	307
Oakland Center	Low GA Transitioning	1,170	11	6.2	1 02	2449	406
Oakland Center	Low GA Low Altitude Through	18,750	188	0 384	0.06	-	-
Kansas City Center	Med GA High Altitude Through	18,200	182	1.68	0 083	8544	412
Kansas City Center	Med GA Transitioning	7,800	78	3.92	0.19	-	-
Houston Center	Med GA Low Altitude Through	9,700	97	0 80	0 08	3034	303
Chicago Center	High GA Transitioning	770	7.7	17	1.4	5382	454
Cleveland Center	High GA Low Altitude Through	3,400	34	4.2	0 40	4360	457

TABLE C-II

SUMMARY OF 1985 TRAFFIC ACTIVITY FORECASTS

Average 1985 Peak Minute GA Aircraft Under Center Surveillance	Average 1985 Peak Minute Military & Air Carrier Under Center Surveillance	Average 1985 Peak Minute GA Spread per 100 nmi^2	Average 1985 Peak Minute Military & Air Carrier Spread per 100 nmi^2	1985 Peak Hour General Aviation Hub Activity	1985 Peak Hour Military & Air Carrier Hub Activity
1139-8544	303-457	0.3-17	0 06-1.4	913-5985	66-502

TABLE C-III

BUSY HOUR OPERATIONS EXTRAPOLATED INTO AIRCRAFT MIX – 1965-1985

Forecast Factor		Highest Activity New York					Moderate Activity Detroit					Minimum Activity Cincinnati				
		1965	1970	1975	1980	1985	1965	1970	1975	1980	1985	1965	1970	1975	1980	1985
Busy Hour Operations	Air Carrier	176	213	277	372	502	40	41	57	69	81	20	27	37	50	66
	GA	1130	1962	2923	4365	5985	408	681	1035	1607	2519	194	249	389	611	913
Air Carrier	A	67	83	107	133	161	10	13	16	18	20	4	7	10	11	12
	B	109	130	170	239	341	30	28	41	51	61	16	20	27	39	54
General Aviation	GA3(C)	7	79	199	360	556	2	30	77	145	236	1	6	16	32	53
	GA1 GA2 (D-E)	1123	1880	2724	4005	5429	406	651	958	1462	2283	193	243	373	579	860
General Aviation to Air Carrier Ratio	GA1, GA2, GA3, Air Carrier	1				12/1	1				31/1	1			18/1	14/1
Air Carrier Growth	GA3, Air Carrier	1				3/1	1				2/1	1			2.5/1	3 3/1
GA Growth	GA1, GA2	1				5/1	1				6/1	1			3/1	4.7/1

VTOL/STOL airports were not considered in the FAA forecasts [Ref 57] and have not been added to the data appearing in Table C-III.

The large hubs which were selected for the aircraft activity forecast were New York, Detroit and Cincinnati. Of the twenty-two large hubs, New York is the most active, Detroit the tenth most active, and Cincinnati the least active.

The number and types of airports vary with each large hub. All air carrier airports are assumed to have ATC manual control towers which are capable of providing departure and approach service. As a result, large hub air carrier airports frequently must support the reliever airports, those airports without departure or approach control. The numbers which precede the airfield designators appearing below indicate the number of airfields of the type listed to be found within the hub.

<u>New York (L) (Highest Activity)</u>

Airport types and number in the hub:

3	AC (T)	(LaGuardia, J. F. Kennedy, Newark)
2	AC (T) R	(Islip, White Plains)
2	GA (T) R	(Teterboro, Morristown)
1	PR	(Linden, N. J.)
6	R	(Caldwell, N. J.)

<u>Detroit (Average Activity)</u>

Airport types and number in the hub:

1	AC (T)	(Metropolitan)
1	AC (T) R	(Willow Run)
2	GA (T) R	(Detroit City, Pontiac Municipal)
1	P	(Pontiac)
2	R	(Grosse Ile/Flat Rock, Plymouth)

Cincinnati (L) (Lowest Activity)

Airport types and number in the hub:

1	AC (T)	(Greater Cincinnati)
1	P R	(New Cincinnati Airport)
1	GA (T) R	(Cincinnati Municipal)

Analysis shows that the activity experienced within the New York Hub during 1965 is representative of what will be experienced at Detroit in 1980. Cincinnati is expected to experience in 1980 the traffic load experienced at Detroit in 1965. Thus it is possible to forecast Detroit's needs of 1980 by looking at New York's problem today. Similarly, a 1980 Cincinnati traffic activity will approximate that of Detroit in 1965. From this discussion it can be seen that if implementation of area navigation capability can solve the traffic saturation problem in New York in 1968, it will provide a 1980 solution for Detroit and Cincinnati. (Recall also that there are 9 hubs larger than Detroit.) The second design implication is that VTOL and STOL aircraft should utilize facilities other than those required by CTOL. Access to rural strips and reliever airports is mandatory.

C.2 NAVIGATION REQUIREMENTS

Navigation requirements, in terms of system 3σ accuracy, are generated from six related sources:

(1) traffic activity forecasts
(2) flight plan control (ETA)
(3) separation standards and surveillance needs
(4) approach and landing criteria
(5) all-weather landing criteria
(6) radar surveillance data complement

The navigation accuracy constraint is given in terms of the vector:

$$\begin{bmatrix} \sigma_{AT} \\ \sigma_{CT} \\ \sigma_{h} \\ \sigma_{A} \end{bmatrix}$$

where σ_{AT} = 3σ along track error

σ_{CT} = 3σ cross track error

σ_{h} = 3σ altitude error

σ_{A} = 3σ heading error.

The navigation equipment accuracy is specified by the above vector. Throughout the derivation of the navigation requirements, the along track, cross track, and altitude components are derived from the following equations:

$$\sigma_{AT} = 1/10 \, s_{AT}$$

$$\sigma_{CT} = 1/10 \, s_{CT}$$

$$\sigma_{h} = 1/10 \, s_{h}$$

where s_{AT} = an along track distance

s_{CT} = a cross track distance

s_{h} = an altitude

The 1/10 factor is used to define navigation equipment errors which will be insignificant with respect to:

(1) flight technical errors

(2) human blunders

(3) display instrumentation, control and guidance errors

This constraint was made significantly stringent so that the requirements would be maximum and safety factors could be incorporated.

C.2.1 Navigation Requirements - Traffic Activity Forecasts

Traffic activity forecast inputs to the definition of navigation requirements were computed from three data sources:

(1) 1985 peak minute density (overs, departures, and arrivals) per 100 square nmi

(2) 1985 peak minute densities (overs, arrivals, departures) under surveillance per ATC center

(3) 1980 peak hour operations (arrivals, departures) within a Large Hub.

The aircraft classes, because of performance limitations or ATC constraints, are restricted to the general speed and altitude regimes:

General Aviation: GA1, GA2

speed $\approx$ 180 kts

altitude $\approx$ 6 kft to 11 kft

Military, Air Carrier, and GA3

(1) speed $\approx$ 300 kts

altitude = 11 kft to 18 kft

(2) speed $\approx$ 600 kts

altitude = 18 kft to 45 kft

Along track and cross track navigation accuracy and performance requirements were derived from the following equations:

$$\sigma_{AT} = 1/10\ s_{AT}$$

$$\sigma_{CT} = 1/10\ s_{CT}$$

s_{AT} = along track separation

s_{CT} = cross track separation

Table XVIII (Section 3.5, Volume II) summarizes the results.

Case 1: Peak Minute 100 sq nmi Density

General Aviation:

(1) g = GA aircraft density

$g < 1$ per flight level

(2) $s_{CT} = 10$ nmi

(3) $s_{AT} = \min\ [\ (5\ \text{min})\ V, \frac{\text{Area}}{g}\ ]$

$g > 1$ per flight level

(4) $s_{CT} = \frac{\text{Area}}{\text{int}\ (g/FL)} \cdot \frac{1}{s_{AT}}$

(5) $s_{AT} = V\ (5\ \text{min})$

where:

Area = 100 sq nmi

V = aircraft speed as a function of altitude regime, 180 kts

FL = number of flight levels, 11 between 6,000 ft and 11,000 ft

min [a, b] implies a or b, whichever is minimum

Air Carrier:

(1) ρ = air carrier and military aircraft density

$\rho < 1$ per flight level

(2) $s_{CT} = 10$ nmi

(3) $s_{AT} = \min\ [\ (ta)\ V, \frac{\text{Area}}{\rho}\ ]$

$\rho > 1$ per flight level

(4) $s_{CT} = \frac{\text{Area}}{\text{int}(\rho/FL)} \quad \frac{1}{s_{AT}}$

(5) $s_{AT} = Vta$

where:

Area = 100 nmi^2

V = aircraft speed; 300 kts (11,000 ft to 18,000 ft), 600 kts (FL 180 to 450).

FL = number of flight levels, 15 and 19 respectively

ta = 5 minutes and 15 minutes per low altitude and high altitude, respectively

Case 2: Center and Hub Aircraft Densities

Arrivals and Departures:

$$s_{AT} s_{CT} = \frac{A}{N} [Ag + Ac + Av + As] [T_D + T_A]$$

where:

A = Hub, Center area nmi^2

N = number of aircraft under surveillance

Ag, Ac, Av, As = number of general aviation and commercial airfields, vertiports and stolports respectively within the Hub

T_D, T_A = number of departure and arrival tracks respectively

Overflights:

General Aviation:

$$s_{AT}\, s_{CT} = \frac{A}{(n_{gI} + n_{gV})} FL$$

where: n_{gI} = number of GA IFR flights

n_{gV} = number of GA VFR flights

FL = number of GA flight levels (10)

$\sigma_{AT} = V$ (in minutes)

Aircarrier and Military:

$$s_{AT}\, s_{CT} = \frac{A\ (FL^{-} + FL^{+})}{(n_m + n_c + n_v + n_s)}$$

where:

n_m = number of military IFR, VFR flights

n_c = number of CTOL IFR, VFR flights

n_v = number of VTOL IFR, VFR flights

n_s = number of STOL IFR, VFR flights

s_{AT} = V (5 minutes), V (15 minutes); low altitude and high altitude respectively.

FL^{-} = number of Flight Levels 11 kft to 18 kft

FL^{+} = number of Flight Levels FL 180 to FL 450

C.2.2 Navigation Requirements - Flight Plan Control

Estimated time of arrival at a fixed waypoint is one of the principal means of coordination between the aircraft flight profile and the traffic control system. The waypoint can be located in the enroute airspace in the terminal area, or in a holding pattern. The pilot complies with the submitted and approved flight plan by monitoring his own ETA to the next waypoint. The traffic control system, for its part, resorts to surveillance data to estimate the aircraft's arrival at the assigned waypoint. When the traffic control system utilizes surveillance data derived from the airborne system as well as ground based computer flight plan data, ETA is the variable which measures system performance.

Errors in the variables used to compute ETA are factors which help to define system requirements. By specifying the tolerance on ETA that is acceptable to the traffic control system for safely controlling the flow of traffic, system requirements can be further specified.

The four geometric systems which are employed by user aircraft are the rho-theta system, along track/cross track system, rhumb line, and great circle system. With suitable signal processing, these coordinate systems generate aircraft steering signals for control of the aircraft in the horizontal plane. Conventional guidance signals which the pilot uses to update the aircraft steering signal are cross track distance or track angle error, both of which are expressions relative to desired course or track. To further determine the aircraft's status along a given track, the pilot requires knowledge of distance-to-go. To comply with a pre-submitted flight plan, the estimated time of arrival at the next waypoint is then computed from distance-to-go, ground speed and present time.

The expression for ETA is derived independently of the navigation system of equations.

$$\eta = \text{ETA}$$

$$\eta = \frac{\text{DTG}}{V} + t$$

$$\text{DTG} = [(\rho_{OD} - x_{AT})^2 + (y_{CT})^2 + (\Delta z)^2]^{1/2}$$

where:

DTG = distance to go

ρ_{OD} = initial leg length

x_{AT} = along track distance

y_{CT} = cross track distance

Δz = altitude difference between aircraft position and waypoint command altitude

t = time

Linearizing the equation, assuming differentials to be gaussian random variables with zero mean, and computing the variance of ETA, yields the error equation:

$$\sigma_\eta = [(C_1 \sigma_t)^2 + (C_2 \sigma_v)^2 + (C_3 \sigma_{AT})^2 + (C_4 \sigma_{\rho_{OD}})^2 + (C_5 \sigma_{CT})^2 + (C_6 \sigma_h)^2]^{1/2}$$

where:

$C_1 \ldots C_6$ are error sensitivity coefficients

$$C_1 = 1$$

$$C_2 = \frac{DTG}{V}$$

$$C_3 = \frac{y_{CT}}{DTG}\left(\frac{1}{V}\right)$$

$$C_4 = \frac{1}{V}$$

$$C_5 = \frac{1}{V}$$

$$C_6 = \left(\frac{\Delta z}{DTG}\right)\left(\frac{1}{V}\right)$$

σ_i → the 3σ parameter of the i^{th} variable

σ_V is in percent

The navigation requirements in terms of cross track error σ_{CT}, and along track error σ_{AT}, can be computed from the error equation. By selecting σ_η, evaluating the coefficients, the system error budget is computed.

To define the navigation equipment errors, a ratio of 1/10 is used. The statistical addition of the navigation equipment errors to other system errors will result in an insignificant contribution from the navigation system. Therefore, the equipment errors will be insignificant when compared to:

(1) flight technical errors
(2) human blunders
(3) display instrumentation, control and guidance errors.

Current air traffic control practice is used to specify ETA. Current IFR flight plans must be maintained to a coordination factor value of ± 3 minutes of ETA. Therefore:

$$\sigma_\eta = 1/10 \text{ ETA}$$

$$= 0.3 \text{ minutes for air carriers}$$

and

$$\sigma_\eta = 1/10 \ (6^*)$$

$$= 0.6 \text{ minutes for general aviation}$$

To evaluate the heading accuracy requirement, the following equation is used:

$$\sigma_A = \frac{\sigma_{CT}}{DTG}$$

To evaluate the ground speed accuracy requirement, the following equation is used:

$$\sigma_V = \frac{\Delta V}{V} \times 100$$

where $\Delta V = 10$ kts, true airspeed

The value of ΔV is based upon the current traffic control practice, viz. that aircraft true airspeed must be within $\pm$ 10 kts below FL 180 and $\pm$ 0.01 Mach no. (approximately 6 kts TAS) for jet aircraft to maintain the IFR flight plan.

Table XIX, Section 3.5, Volume II summarizes the results. Table C-IV presents the sensitivity coefficients which were computed for the following data.

Case 1: GA1, GA2

Conditions for computing general aviation requirements are:

(1) VFR controlled airspace

(2) $V = 150$ kts

(3) DTG = 20 nmi, based on VOR(T) nominal range

(4) track angle = 2°

* Representative of the capability of General Aviation VFR-rated pilots.

TABLE C-IV

NAVIGATION SYSTEM REQUIREMENTS - ETA SENSITIVITY FACTORS

Sensitivity Factor / User	ETA Time Synch	ETA Speed Error	ETA Cross Track Error	ETA Leg Length Error	ETA Along Track Error	ETA Altitude Error	σ_{η}	User Requiremen σ_{CT} nmi	σ_{AT} nmi	σ_A deg
GA1, GA2	1	8	0 014	0.40	0 40	3×10^{-7}	0 6	0 5	0 5	1 4°
GA3, CTOL Jet VTOL, STOL, SST (Low altitude enroute)	1	7	0.007	0 20	0 20	10^{-7}	0 33	0 5	1 1	0 8°
GA3, CTOL Jet, VTOL, STOL (High altitude enroute)	1	4 7	0 005	0.13	0.13	10^{-7}	0 33	0.5	2 3	0 8°
SST	1	20	0.002	0 05	0 05	$0 5 \times 10^{-7}$	0.33	1 6	4 4	0 15°

Also for terminal area with Alt < 10,000 ft. equal to low altitude enroute

Case 2: GA3, CTOL, STOL, VTOL, SST (low altitude)

(1) IFR in low altitude (12,000 ft to FL 180) controlled enroute airspace

(2) IFR in high altitude (FL 180 to FL 450) in controlled enroute airspace

(3) V = 300 kts (low altitude)

(4) V = 480 kts (high altitude)

(5) DTG = 35 nmi, based on VOR(L) nominal range

(6) track angle = 2°

Case 3: SST

(1) IFR in high altitude (> FL 450) controlled airspace

(2) V = 1200 kts

(3) DTG = 600 nmi, based on report points every 10° of longitude

(4) track angle = 2°

C.2.3 Navigation Requirements - Separation Standards and Surveillance Needs

Navigation requirements can be further derived from traffic control separation requirements which are specified in traffic control procedural manuals. The FAA establishes separation requirements throughout all controlled airspace, terminal area departure and arrival, holding patterns and enroute airspace. Factors which determine the separation requirement values include these: (1) whether traffic is converging or diverging; (2) whether traffic is crossing at the same altitude levels; and (3) relative speeds (rate of closure) of all same-track aircraft. Separation requirements, expressed in terms of cross track separation (nmi), along track separation (minutes), and altitude separation (ft) are translated into navigation accuracy requirements by applying the 1/10 ratio. These requirements, in terms of time, become navigation requirements if the vehicle speed is known.

Thus,

$$\sigma_{AT} = 1/10 \; s_{AT}$$

$$\sigma_{CT} = 1/10 \; s_{CT}$$

$$\sigma_{h} = 1/10 \; s_{h}$$

where:

$s_{AT} = V \, T_{AT}$

s_{AT} = along track separation distance

T_{AT} = along track separation time

s_{h} = altitude separation distance

V = aircraft speed

The rationale for using existing separation requirements to aid in defining NAVTRACS navigation requirements is that the separation requirements have evolved from the existing safe system. Other alternatives (Section 3.1.4.2) can increase system capacity without extensive changes in the safe separation standards. Therefore, the navigation data, linked to the ground system, refines aircraft surveillance data for all aircraft cross sectional area and weather conditions. This can do much to decrease the controller's workload, and leads to increased capacity. Therefore, separation requirements of the existing system supply a realistic input to the definition of navigation requirements.

Table XX (Section 3.5, Volume II) summarizes the navigation requirement factors that are derived from separation standards and surveillance data.

C.2.4 Navigation Requirements - Approach and Landing Criteria

Another input to the definition of navigation requirements is provided by approach and landing requirements. As a minimum, the navigation system must provide accuracy sufficient to permit the pilot to fly the aircraft to a point where the landing aid is intercepted. The envelope of this point, then, serves as one measure in defining the navigation system accuracy requirement. This approach-related requirement becomes a tighter constraint on the total navigation system requirement if the accuracy of the navigation system must also be acceptable for landing. The landing requirement is derived from the size of the runway width or the VTOL pad diameter. The accuracy requirement in both cases must specify a sufficiently broad spectrum of signals to properly drive the aircraft dynamics.

Thus, for approach,

$$\sigma_{AT} = 1/10 \; s_{AT}$$

$$\sigma_{CT} = 1/10 \; s_{CT}$$

$$\sigma_{h} = 1/10 \; s_{h}$$

where: s_{AT} = along track spacing set by approach control

s_{CT} = cross track distance at a point in the landing beam envelope

s_{h} = vertical distance at a point in the landing beam envelope

<u>Case 1: AILS Geometry</u>

At 15 nmi from the runway, the glideslope envelope requirements are:

$$s_{CT} = \pm \; 0.6 \text{ nmi}; \quad s_h = \pm \; 400 \text{ ft}$$

<u>Case 2: ILS Geometry</u>

At 20 nmi from the runway, the glideslope envelope specifies:

$s_{CT} = \pm\ 3.3$ nmi

$s_h = \pm\ 400$ ft

For landing, the runway and pad sizes set the requirement:

STOL, CTOL, SST, GA3 runway width = 150 ft

VTOL landing pad diameter = 50 ft

Tables XX and XXI, Section 3.5, Volume II, summarize the navigation requirement data generated by the approach and landing constraint.

C.2.5 Navigation Requirement - All-Weather Landing Criteria

Positional navigation requirements can be derived from the all-weather landing requirements. The legal minima for instrumented runways specify runway visual ranges and action decision heights for all-weather landing. The runway visual ranges and decision heights can be translated into along-track navigation requirements; the decision height into altitude requirements. The runway width, or VTOL pad diameter, determines cross-track constraints.

Thus,

$$\sigma_{AT} = 1/10\ s_{AT}$$

$$\sigma_{CT} = 1/10\ s_{CT}$$

$$\sigma_h = 1/10\ s_h$$

where: s_{AT} = runway visual range

s_{CT} = runway width, or VTOL pad diameter

s_h = decision height

Table XXI, Section 3.5, Volume II, summarizes the all-weather landing requirement.

C.2.6 Navigation Requirement - Taxiway Requirement

Another input to the specification of navigation requirements is taxiway width. CTOL, STOL, SST and GA3 taxiways are nominally 75 ft wide. The taxiway width of a typical vertiport is predicted to be 50 ft. The navigation requirement, then, is:

$$\sigma_{AT} = 1/2\ s_{CT}$$

$$\sigma_{CT} = 1/2\ s_{CT}$$

where: s_{CT} = taxiway width

These navigation requirements are tabulated in Table XXI , Section 3.5, Volume II.

C.2.7 Navigation Requirement - Accuracy Relative to Surveillance Radar

Navigation requirements are also determined by the accuracy attained by surveillance radars. As a minimum, an advanced area navigation/traffic control system would supplement the radar surveillance data with the airborne derived aircraft position data. Such a service would afford completeness in coverage for varying weather conditions and varying cross sectional areas. The radar surveillance data, range and bearing, must be converted to position information in the aircraft geometric system of navigation. The position accuracy is the factor providing the navigation requirement constraint.

Thus,

$$\sigma_{AT} = \sigma_{CT} = \sigma_{RADAR}$$

where: σ_{RADAR} = 3σ aircraft position error derived from radar data.

Radar Surveillance Fixing Errors:

Component errors:

Surveillance radar azimuth angle error

Surveillance radar siting error to True North

Train and elevation siting errors

Vertical anomalies in siting

Radar range resolution

Radar site/center parallax errors

Radar siting errors to center

Processing:

Beacon processing

Primary radar processing

Display:

Display range resolution

Display bearing resolution

Display trace area

Display trace electronic processing

Tie-in to Area Navigation System

Relative position errors to the center.

The following errors are typical of current ATC equipment:

ASR-4 (S band)

Beamwidth 1.2°

Range Resolution 0.083 nmi.

Targets on scope

707-727 aircraft bloom to 3.5° bearing and 0.5 to 0.75 nmi range

Controller can see center of target to 1° azimuth and 0.062 nmi range

ARSR (L band)

Beam width 2°

Range Resolution 0.167 nmi

Targets on scope

5° bearing

1 nmi range

Controller can read center of target to 1.5° to 2° azimuth and 0.125 to 0.25 nmi range.

Beacon Processing of Secondary Radar

Center digitally to ± 0.25°, range to 0.033 nmi.

With improvements to ± 0.25°, range to 0.01 nmi.

Radar Processing

Bearing to 0.20° and range to 0.062 nmi.

The Flight Information Manual requires fixing to CEP = (500 ft, 3% R) whereR is range to known station. Experimental data shows a JFK fix of 1 nmi at 105 nmi.

Table C-V summarizes the worst case conditions. The ARSR target is 200 nmi from the surveillance radar, and the ASR target is 50 nmi from the surveillance radar.

Table XXII, Section 3.5, Volume II summarizes this particular navigation requirement.

Table C-V
RADAR FIXING ACCURACY

Radar	Case	1σ Aircraft Position Error
ARSR	At Site	3 6 nmi
	At Center	3.6 nmi
	Processing	3 6 nmi
	Display	8.5 nmi
ASR	At Site	0.7 nmi
	At Center	0 7 nmi
	Processing	0.8 nmi
	Display	2.7 nmi

C.3 COMMUNICATION REQUIREMENTS

Air Traffic Control system communications include air-to-ground surveillance reports, requests for acknowledgement of commands, identification, and advisory messages. The ground-to-air messages include command, acknowledgements, identification and advisory messages. Section 3.6, Volume II, defines message content and bit requirements.

Bandwidth requirements depend upon the number of users in the system at a given instant of time. The system communications capacity in bits/sec is computed from the number of users in the system at a given instant of time, the user speed and the airspace in the terminal area. The airspace is organized into arrival, departure and enroute tracks.

C.3.1 Communication System Capacity

The system capacity is defined by the equation:

$$C = \frac{N_A \text{ (Bits per user)}}{\text{Interrogation Rate}}$$

where:

C = system capacity in bits/sec

N_A = number of instantaneous users requiring service

The interrogation rate is the time interval required by the traffic control and surveillance system to adequately define vehicle position – both present position and forecast position. Rates differ according to type of aircraft class.

Air carrier C = 1,000 bits/sec
General Aviation C = 21,000 bits/sec
} as developed in the following subsections

C.3.1.1 Number of Users Requiring Service

The number of users requiring service, N_A, is computed in a steady state system from the peak hour operations expected in the system. It can be shown that . . .

$$N_A = \frac{L\,\mathring{N}}{V}$$

where: $\mathring{N}$ = busy hour operations

V = steady state speed

L = the length of arrival, departure and enroute tracks in the terminal area, nominally 50 nmi

The worst case, as presented in Table C-3, is given by the busy hour operations, expected in New York in 1980.

$\mathring{N}$ = 372 (air carrier)

$\mathring{N}$ = 4,365 (general aviation)

The operations are divided into arrivals, departures, low enroute and high enroute code settings.

C.3.1.2 Interrogation Rate

The interrogation rate strongly influences the data link bandwidth requirements. Tradeoffs to decrease the interrogation rate for a single aircraft include:

(1) Code set - arrivals, departures, ground traffic, enroute-low, enroute-high, flight level

(2) Ground system dead reckoning - ground computation of aircraft position computed from the last surveillance report, and the aircraft flight plan

(3) Compliance with the flight plan - per the Limit Logic concept which enables tighter flight plan tolerance

(4) Channel allocation

Table C-VI summarizes the interrogation rate tradeoff based on ground dead reckoning.

TABLE C-VI
TERMINAL AREA INTERROGATION RATES

Code Unit	Speed	Interrogation Rate - sec - Sampling Criteria		
		0.1 nmi min accuracy	GND DR 1 nmi	GND DR 2 nmi
Arrival-Destination	300 kts (0.14 nmi/sec)	1	7	14
Departure-Destination	300 kts (0.14 nmi/sec)	1	7	14
Enroute-Low	300 kts (0.14 nmi/sec)	1	7	14
Terminal Area	150 kts (0.04 nmi/sec)	2.5	25	50

For comparison, the sampling rate of Secondary Surveillance Radar is:

$$6 \text{ rev/min} = 10 \text{ sec}$$

$$18 \text{ rev/min} \approx 3 \text{ sec}$$

A nominal interrogation rate of 10 sec for both general aviation and air carrier aircraft has been used for the purposes of the following calculators.

C.3.1.3 Data Link Bandwidth Requirements

Case 1: General Aviation

Speed: 150 kts

N_A: 1455

Message Content: 145 bits (Section 3.6)

C = 21,000 bits/sec

Case 2: Air Carrier

Speed: 300 kts

N_A: 62

Message Content: 162 bits (Section 3.6)

C = 1,000 bits/sec

These bandwidth requirements are worst case conditions, but can be accommodated with a VHF channel and certainly a UHF channel. Tradeoffs in interrogation rates and in message content can reduce the required communication capacity of general aviation aircraft to 4,000 bits/sec.

APPENDIX D

PILOT WORKLOAD ANALYSIS

To understand the need for automation of navigation and communication functions and equipment operation, it was necessary to develop an appreciation of the tasks performed today by aircrew personnel in managing their aircraft.

The workload methodology was based on four sources of information: synthesized task times experimentally determined in pilot studies (Ref. 75) which specify pilot task time in performing mechanical functions; results of a series of field trips in which aircrew personnel were carefully questioned about the manner in which they performed their jobs; the refinement of certain workload and pilot utilization estimators developed by personnel of this organization; and data obtained from a series of simple, timed, paper and pencil tests utilizing a paper cockpit mockup. The subjects were licensed aircrew personnel, each of whom had significant experience with the tasks under investigation.

The resulting information provides the baseline workload estimates for the remainder of the study, aspects of which are reported on elsewhere in this document.

Two present-day aircraft, a four-engine CTOL jet transport and a single-engine GA2 aircraft, provided the baseline information. The pilot tasks in the CTOL jet were assumed to be sufficiently like those of the sophisticated GA3 aircraft that an assessment of GA3 was not made. Task times for GA2 aircraft were assumed to be sufficiently like those of GA1 that a separate workload assessment was felt not to be necessary.

Operator tasks and task times for the VTOL and STOL aircraft were developed from a review of NASA documents and similar literature. Workload for the SST aircraft was developed from an extrapolation of operational experience of PNSI personnel, review of

ARINC documents and airframe manufacturers' documents, and the results of an on-going, in-house study of Concorde performance utilizing an IBM 360-44 computer. In summary, pilot monitor and control workload estimates were prepared for four aircraft types (Tables D-VII, D-VIII, D-IX and D-X); task times were estimated for the communications task (Tables D-V and D-VI); and for twenty navigation-related tasks (Table D-III).

D.1 PILOT/WORKLOAD MODEL

The pilot workload analysis requires a model of the human operator. Pilot performance was evaluated for the aircraft control and monitor, navigation management and pilot/ATC communications tasks utilizing the rationale presented in the following paragraphs. Experienced aircrew personnel were utilized as subjects.

D.1.1 Operator Transfer Function

Reference 76 provides a general low-bandwidth system transfer function:

$$G(s) = \frac{K\,(1 + \tau_A s)\, e^{-Ds}}{(1 + \tau_L s)\ (1 + \tau_N s)}$$

where τ_A = operator anticipation time constant, 0 to 2.5 sec.

τ_L = operator error smoothing lag time constant, 0 to 20 sec.

τ_N = operator short neuromuscular delay, 0.08 to 0.12 sec.

K = operator gain, 1 to 100

D = operator transportation lag, 0.16 to 0.24 sec.

Generally, this linearized transfer function provides a model of a motivated, well-trained operator in performing simple tasks such as closed loop tracking utilizing compensatory displays.

Event sequence times, incorporating the visual, manual and audio task times, were developed for this study from extensive operational experience.

D.1.1.1 Human Response Times

The time delay is given by time elapsing prior to pilot responding to display information [Ref 71]:

Reaction time depends on:

Age: 20-40 years, Sense: aural visual, Stimulus intensity, Practice, Preparedness, Motor Unit responding	0.23 to 0.30 seconds

Speed of Perception to Action:

Brain perception of what eye sees	0.1
Cognition	0.4
Decision	4-5
Motor response	0.5
Vehicle reaction	2+
	7-8 seconds

Man's Response Latency:

Go/No Go situation	0.2
Response rate for successive stimuli	0.1
Reaction time for simple muscular movement	0.22
	0.5 seconds

D.1.1.2 Operator Execution Times

Table D-1 lists operator execution times and standard deviations for the execution times [Ref 75] used in development of the pilot workload estimates appearing in this Appendix.

TABLE D-1
OPERATOR EXECUTION TIMES

Operator Action	Average Execution Time sec.	Average Standard Deviation sec.
Set Toggle Switch	1.1	0.76
Set Detent Selector Switch	2.1	0.51
Set Rotary Control	8.6	3.00
Set Thumbwheel	8.6	3.00
Push Button (or Foot Switch)	4.2	1.02
Key Board Push Button, N digits	3.2 + 1.1 N	1.1 + 0.4 N
Lever (Throttle Setting)	3.0	0.48
Joy Stick Setting	3.8	0.48
Read Instruments, N Instruments	0.6 N + 0.6	0.2 N + 0.2
Communication, N Words	0.66 N + 0.6	0.34 N + 0.4
Ignore Nonessential Subtask when Situation is "Highly Urgent"	0.6	

D.1.1.3 Synthesized Task Times

Operator experience in association with the above execution times, visual scan times, communication times and response times were combined to provide the navigation management, communication management and pilot task times.

Task times were developed and then subjected to review by experienced professional airmen.

D.1.2 Operator Workload Model

Two figures of merit were applied to quantify workloading:

(1) task time

(2) operator % utilization

Workloading was first assessed for operator defined task times. Subsequently, a figure of merit was devised based on % utilization of the operator's faculties. This figure of merit was computed from the equation:

$$(1) \quad \% \text{ Utilization} = \frac{\text{Task Utilization}}{\text{Total Utilization}} \times 100$$

where Task Utilization = weighting factor per task;

Total Utilization = weighting factor for % utilization of the operator's total faculties

Table D-II identifies the weighting factors.* As an example, the task which requires one hand and voice use yields:

$$\% \text{ Utilization} = \frac{15}{28} \times 100 = 54\%$$

Total utilization depends on crew composition and crew functions.

Use of total faculties dictates that:

Pilot/Copilot Total Utilization = 28

Navigator Total Utilization = 20

* Reference (77) substantiates these weighting factors.

TABLE D-II
OPERATOR UTILIZATION CHART

Task Combination

Faculty Utilization											
Indirect/Peripheral Vision		x					x			x	
Direct Vision			x					x			x
1 Hand						x	x	x			
2 Hands									x	x	x
2 Feet					x						
Voice				x							
Aural	x										
Task Weighting	1	2	3	4	5	6	7	8	9	10	11

Faculty Utilization										
Indirect/Peripheral Vision		x				x			x	
Direct Vision			x				x			x
1 Hand					x	x	x			
2 Hands								x	x	x
2 Feet	x	x	x	x	x	x	x	x	x	x
Voice				x						
Aural	x									
Task Weighting	12	13	14	15	16	17	18	19	20	21

Faculty Utilization									
Indirect/Peripheral Vision	x				x			x	
Direct Vision		x				x			x
1 Hand				x	x	x			
2 Hands							x	x	x
2 Feet			x						
Voice									
Aural	x	x	x	x	x	x	x	x	x
Task Weighting	12	13	14	15	16	17	18	19	20

Faculty Utilization																	
Indirect/Peripheral Vision	x				x			x		x			x			x	
Direct Vision		x				x			x		x			x			x
1 Hand				x	x	x						x	x	x			
2 Hands							x	x	x						x	x	x
2 Feet			x							x	x	x	x	x	x	x	
Voice	x	x	x	x	x	x	x	x	x								
Aural										x	x	x	x	x	x	x	x
Task Weighting	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28

Faculty Utilization								
Indirect/Peripheral Vision	x			x			x	
Direct Vision		x			x			x
1 Hand			x	x	x			
2 Hands						x	x	x
2 Feet	x	x	x	x	x	x	x	x
Voice	x	x	x	x	x	x	x	x
Aural								
Task Weighting	21	22	23	24	25	26	27	28

To compute average % utilization for a series of tasks, the operator utilization must be averaged over the complete task interval. Therefore:

$$\text{(2)}\quad \text{Average \% Utilization} = \frac{1}{T}\int_{o}^{T} U\,dt$$

where T = the total period

U = task utilization factor in terms of percentage

D.2 NAVIGATION MANAGEMENT - TASK, EXECUTION TIME AND % UTILIZATION ESTIMATES (See Table D-III and D-IV)

All task times and workload assessments reported in this study were based on carefully evaluated opinion of experienced aircrew members. Utilization of the private pilot in the performance of comparable tasks was increased by a factor of one-third to one-half, depending upon an assumption regarding experience and proficiency of the pilot. The effect on task times of inflight emergencies was not considered.

D.3 COMMUNICATION TIMES - NON-AUTOMATED SYSTEM (See Table D-V)

The communication times appearing in Sections D.3.1 and D.3.2 are the baseline estimate for message times for the Event Sequence Diagrams shown in Appendix A.

D.3.1 Typical Air-to-Ground and Ground-to-Air Communication Times for VFR Flights

The use of voice air-to-ground (A-G) and ground-to-air (GA) communications is now the standard means of transferring data from the pilot to the controller and vice versa. As radio frequencies become more congested, the total time a frequency is in use for A-G and G-A communications becomes a matter of concern. This section gives typical examples of A-G and G-A communications occuring on a VFR flight. The execution time for these A-G and G-A communications is also listed. (See Table D-V.)

TABLE D-III

NAVIGATION MANAGEMENT TASK SUMMARY

Minimum Automation Navigation Management Event	Task Time, sec. Ave.	Min.	% Utilization Pilot	Navigator
In Flight Weather Evaluation	794	395	26.6	37.33
Inertial Navigation System Management	597	238	32.6	45.71
Doppler/Computer System Management	819	492	27.4	38.4
Loran A Manipulation	220	94	35.8	50.1
Loran C	265	255	26.3	36.8
Automatic Direction Finder	234	134	28.6	40.0
Fixing Radar	416	244	31.7	44.4
Weather Avoidance Radar	179	86	27.4	38.3
VOR/DME	245	139	26.5	37.1
CLC Management	194	117	23.9	33.5
Determination of Magnetic Course	146	72	33.4	47.5
Altitude Change Enroute	168	99	26.1	36.6
Monitoring Flight Plan Enroute (Fuel Management)	455	170	39.3	55.0
Copying and Acknowledging ATC Clearances (Oceanic)	124	59	28.6	40.0
Turbulence Penetration	17	9	19.4	27.9
Reroute by ATC During Enroute Phase	353	200	31.6	44.2
Radar Identification in Transition Zone	92	74	28.6	40.0
Altitude Change in Transition Zone	55	34	26.8	37.5
Navigation Management in Transition Zone	745	466	34.4	48.2
*Navigation Management of MMD	73	73	28.6	40.0

*No track monitor function

D.3.2 Typical A-G and G-A Communication Times for IFR Flights

Table D-VI gives examples of typical A-G and G-A voice communications required for navigation and control of the aircraft during a typical IFR flight.

D.4 PILOT CONTROL AND MONITOR TASKS

Tables D-VII through D-XI tabulate pilot and copilot manual control and visual tasks. The event times relate to the missions and aircraft flight profiles illustrated in Section 2. Communication and navigation management tasks are purposely omitted from the scheduled tasks, so that an estimate of the residual workload experienced by the

TABLE D-IV
NAVIGATION MANAGEMENT - MINIMUM AUTOMATION

Event	Task	Time	Utilization Factor
In Flight Weather Evaluation	Check Time	1.2	3
	Check a/c position	1.8	3
	Make in flight weather observation	10	3
	Record	15-30	8
	Make in flight weather measurements (temp; w/v)	1 8-60	3
	Record	5-10	8
	Report	25-60	2
	Get forecast (either previously obtained or by radio)	30-300	8
	Modify forecast	60-120	11
	Modify ground speed if necessary	15	11
	Modify eta as necessary	60	11
	Modify fuel calculators	60-120	11
	Recalculate drift (general aviation)	45	11
	Recalculate hdg. (general aviation)	5-60	11
	Copy forecasts	60-300	8
	Ave	794 sec	
	Max	1030	
	Min	395	
	Pilot/Copilot		26 6%
	Navigator		37.3%

Event	Task	Time	Utilization Factor
Inertial Navigation System Management	Switch on to stand by	1.1	8
	Align mode, gyro compass, nav mode	2.2	8
	Program way point(s)	42 ea	8
	Plot DR position	20	11
	Determine external fix	8-180	11 *
	Plot fix LOP's ie. VOR/DME, loran. Record and check time	3.2	11
	Determine DR position error North/South and East/West	20-30	8
	Determine along track error	20-30	11
	Determine across track error	20-30	11
	Determine track angle error	15	11
	Update present position by inserting correct co-ordinates while on memory	43.3	8
	Correlate magnetic heading with platform true heading	10-30	3
	Check eta way point	30-90	11
	Record	3-5	8
	Ave	430 sec	
	Max	522	
	Min	238	
	Pilot/Copilot		32 6%
	Navigator		45 71%

*Present position plus eight waypoints may be programmed in ARINC 561 INS

Event	Task	Time	Utilization Factor
Doppler/Computer System Management	Switch on	2.2	8
	Test	240	7
	Slew ground speed and drift	4	7
	Set required course	10-30	8
	Set required distance	10-30	8
	Determine system tracking error (STE)	15	11
	Offset computer for STE	4.3	8
	Check hdg.	1.2	3
	Check drift	1.2	3
	Check track angle settings	1.8	3

Event	Task	Time	Utilization Factor	
Doppler/Computer System Management (Cont'd)	Check distance settings	1.8	3	
	Determine fix (Rho-theta, hyperbolic)	8-180	8-11	
	Plot DR position	20	11	
	Plot fix	60-240	11	
	Revise STE (across track error)	30-60	11	
	Determine along track error	10-30	11	
	Calculate course change	10-45	11	
	Initiate course change	4 3	8	
	Correlate hdg, drift, and track in auto coupled mode	7 4-10	3	
	Reset distance along track	4 3	8	Update
	Reset cross track indication	4 3	8	
	Reset required track, trouble shoot	4 3	8	
	Recycle breakers	4 2 ea.	8	
	Switch off and on	1.1	8	
	Check eta way point	30-90	8	
	Record	3-5	8	
	Ave	819 sec		
	Max	1034		
	Min	492		
	Pilot/Copilot		27.4%	
	Navigator		38.4%	

Event	Task	Time	Utilization Factor	
Loran A Manipulation	Switch on	1 1	7	
	Estimate DR position for fix	10-30	11	
	Predict relative signal strength and sky ground wave mix for one chain	10-60	11	
	Match pulses	30-180	11	
	Read time difference and record	4 2-10	8	
	Determine and apply sky wave corr.	20	11	
	Read and record time and doppler distance	8.4-15	11	DR pos.
	Add cross track if applicable	10	11	
	Plot LOP	10-30	11	
	Ave	220sec		
	Max	346.*		
	Min	93 7		
	Pilot/Copilot		35 8%	
	Navigator		50.1%	

Event	Task	Time	Utilization Factor
Loran C	Switch power - ON	1 1	7
	Estimate DR position for a fix	10-30	11
	Warm up	300	0
	*Select chain	2.1	8
	*Select Loran C	2 1	7
	*Set bandwidth control - narrow	2 1	7
	*Set function switch - M	2 1	7
	*Set readout switch - A/B	2.1	7
	*Select timebase - 1	2.1	7
	Slew master pulse groups to left of scope	10	8
	Set bandwidth control - wide	2 1	7
	Select timebase - 2	2.1	7
	Align master pulse with gates	20	8
	Select timebase - 3	2 1	7
	Align gate with third cycle of first pulse	20	8
	Set function switch - A	2 1	7

TABLE D-IV (cont'd)
NAVIGATION MANAGEMENT - MINIMUM AUTOMATION

Event	Task	Time	Utilization Factor
Loran C (cont.)	Set readout switch - A	1.1	7
	Set Bandwidth control - narrow	2.1	7
	Select timebase - 1	2.1	7
	Slew until approximate time difference appears on readout	10	8
	Slew pulse groups to left of scope	10	8
	Set bandwidth control - wide	2.1	7
	Select timebase - 2	2.1	7
	Align pulses with gates	20	8
	Select timebase - 3	2.1	7
	Align gate with third cycle of first pulse	20	8
	Record time difference	10	8
	Set function switch-B	2.1	7
	Set readout switch-B	1.1	7
	* Can be accomplished during warm up period		
	Set bandwidth control - narrow	2.1	7
	Select timebase - 1	2.1	7
	Slew until approximate time difference appears on readout	10	8
	Slew pulse groups to left of scope	10	8
	Set bandwidth control - wide	2.1	7
	Select timebase - 2	2.1	7
	Align pulses with gates	20	8
	Select timebase - 3	2.1	7
	Align gate with third cycle of first pulse	20	8
	Record time difference	10	8
	Plot position	20	11
	Ave	565	
	Max	575	
	Min	555	
	Pilot/Copilot		26.3%
	Navigator		36.8%

Event	Task	Time	Utilization Factor
Automatic Direction Finder	Set switches on ADF as required	10	8
	Select frequency	10-20	8
	Identify stations	10-60	0
	Switch function to ADF	1.1	7
	Read ADF bearing and record	5-10	8
	Read time and record	3.2	8
	Determine local grivation and deviation for plotting	10	8
	Add 180° for bearing to plot if necessary	5	8
	Align plotter to grid north	5	11
	Determine DR position and record		
	auto -	5-10	8
	manual -	60-180	11
	Plot LOP	10-20	11
	Ave	234 sec	
	Max	334	
	Min	134	
	Pilot/Copilot		28.6%
	Navigator		40.0

Event	Task	Time	Utilization Factor
Fixing Radar	Set CRT intensity	10	8
	Set tilt	5	8
	Set gain	10	8
	Select appropriate range	5	8
	Tune for ground return	30	8
	Adjust azimuth cursor on template	10-30	8
	Correlate with map	60-240	11
	Identify return	20	8
	Measure relative heading	5-10	8
	Check a/c heading grid or mag	1.2-3	8
	Determine bearing to plot and record	10-30	11
	Determine range and record	10-30	11
	Check a/c altitude above ground	1.2-30	8
	Determine ground range	30-60	8
	Read and record DR pos	3.8-10	11
	Read and record time	3.2-5	8
	Plot LOP and range	30-60	11
	Ave	416 sec	
	Max	588	
	Min	244	
	Pilot/Copilot		31.7%
	Navigator		44.4%

Event	Task	Time	Utilization Factor
Weather Avoidance Radar	Set CRT intensity	10	8
	Set CRT tilt	5	8
	Set CRT range	5	8
	Set CRT gain	10	8
	Tune for echo	30-120	8
	Set for contour	1.1	7
	Select detour heading	10-30	3
	Steer heading		
	manual -	10-60	11
	auto -	5-30	8
	Ave	179 sec	
	Max	271	
	Min	86	
	Pilot/Copilot		27.4%
	Navigator		38.3%

Event	Task	Time	Utilization Factor
VOR/DME	Select station(s)	5-20	3
	Set frequencies VOR/DME	8.6	8
	Identify station(s)	5-30	0
	Set desired radial	4.3-8.6	8
	Observe localizer needle or track bar	1.2-3	3
	Adjust heading as necessary	5-10	8
	*Correlate nav/computer distance to go with DME distance and record	1.8	8
	Amend computer distance as req'd	4.3	8
	Read and record VOR radial and DME range	5-10	8
	Determine, read and record DR position		
	auto-	5-10	8
	manual -	60-180	11
	Read and record time	4.2	8
	Plot range and bearing	30-60	11
	Ave	245 sec	
	Max	376	
	Min	139	
	Pilot/Copilot		26.5%
	Navigator		37.1%

*If headed toward or away from VORTAC

TABLE D-IV (cont'd)
NAVIGATION MANAGEMENT - MINIMUM AUTOMATION

Event	Task	Time	Utilization Factor
CLC Management	Select station(s)	15-45	3
	Determine offset radial & distance	30-90	11
	Program offset radial and distance	8.6	8
	Set VOR/DME frequencies	4.3-8.6	8
	Identify station(s)	5-30	1
	Set desired magnetic course	4.3	8
	Observe localizer needle or HSI	1.2	3
	Compare DME and computer distance if headed toward or away from station	1.8	3
	Correct computer distance as necessary	4.3	8
	Read and record DR position	3.8	8
	Read and record time	3.2	8
	With dual VOR/DME fit determine Rho-theta fix from independent source	5-10	8
	Correlate with CLC derived DR pos.	30-60	11
	Ave	194 sec	
	Max	271	
	Min	117	
	Pilot/Copilot		23.9%
	Navigator		33 5%

Event	Task	Time	Utilization Factor
Determination of Magnetic Course	Enter tables and/or radio nav. charts	60-180	11
	Manual-measurement with plotter and application of variation or grivation		11
	Measure grid course or true course	5-10	11
	Apply griv/variation to grid or true course	2-5	8
	Record	5-10	8
	Ave	146 sec	
	Max	205	
	Min	72	
	Pilot/Copilot		33.9%
	Navigator		47.5%

Event	Task	Time	Utilization Factor
Altitude Change Enroute	Initiate request for clearance or answer I D. call from ATC	25-60	8
	Request altitude change or receive ATC change	30-60	6
	Acknowledge receipt of clearance and report leaving level	10-30	8
	Initiate auto pilot climb/descent or manually adjust control column	3.8	8
	Adjust throttles (climb/descent)	3-20	8
	Check through various altitudes as required by ATC	10-20	6
	Adjust throttles upon reaching new level	3-20	8
	Advise ATC upon reaching if required	10-20	6
	Level off on auto pilot or manually adjust control column	3 8	8
	Ave	168 sec	
	Max	238	
	Min	99	
	Pilot/Copilot		26 1%
	Navigator		36 6%

Event	Task	Time	Utilization Factor
Monitoring Flight Plan Enroute (Fuel Management)	Revise eta destination ie compare way point eta's and ata's	10-160	11
	Determine fuel on board and record with time	20-240	11*
	Determine burn off	10-20	11
	Compare with planned burn off	10-20	8
	Establish expected fuel consumption ahead	60-180	11**
	Determine fuel over destination ie FOD	60-120	11
	Ave	435 sec	
	Max	740	
	Min	170	
	Pilot/Copilot		39.3%
	Navigator		55.0%

*Dependent on number of fuel tasks

**Depends on cruise control methods, ie. HSC or LRC weight, etc.

Event	Task	Time	Utilization Factor
Copying and Acknowledging ATC Clearances (Oceanic)	Make contact with appropriate ATC agency (ie Center, terminal)	10-45	8
	Copy clearance as received	30-90	8
	Acknowledge clearance (ie read back)	10-45	8
	Change back to appropriate frequency	8.6	8
	Ave	124 sec	
	Max	189	
	Min	59	
	Pilot/Copilot		28 6%
	Navigator		40.0%

Event	Task	Time	Utilization Factor
Turbulence Penetration	Adjust throttles	3-20	11
	Check mach meter	2.4	3
	Check IAS indicator	2 4	3
	Check altimeter	2.4	3
	Check placard turbulence penetration speed	1 2	3
	Auto pilot in alt. hold	1.1	8
	Disconnect alt hold in moderate turbulence	1.1	8
	Ave	21 8 sec	
	Max	30 6	
	Min	13 6	
	Pilot/Copilot		19.9%
	Navigator		27.9%

Event	Task	Time	Utilization Factor
Altitude change in transition* zone	Acknowledge clearance and report leaving present level	10-15	7
	Initiate auto pilot climb descent or manually adjust control column	3 8	8
	Adjust throttles	3-20	8
	Level off on auto pilot or manually adjust control column	3.8	8
	Adjust throttles upon reaching new level	3-20	8
	Report reaching new level	10-15	6
	Ave	56 sec	
	Max	78	
	Min	34	
	Pilot/Copilot		26.8%
	Navigator		37.5%

*Oceanic/Continental Transition

TABLE D-IV (cont'd)
NAVIGATION MANAGEMENT - MINIMUM AUTOMATION

Event	Task	Time	Utilization Factor
Radar identification in the transition* zone	Make contact with appropriate ATC center when in VHF range	10-15	8
	Code identification on transponder	4.3	8
	Receive and copy ATC clearance as applicable (Airways, direct route)	30-45	8
	Read back ATC clearance	30-45	8
	Ave	91.8 sec	
	Max	109	
	Min	74	
	Pilot/Copilot		28 6%
	Navigator		40 0%

*Oceanic/Continental Transition

Event	Task	Time	Utilization Factor
Reroute by ATC in Enroute Phase	Acknowledge ATC call	10	6
	Copy clearance	30-45	8
	Read back clearance	30-45	8
	Program crew way point:		
	(1) INS		
	Determine co-ordinates	30-120	11
	Program co-ordinates	10-30	8
	Alter course ref to HSI	10-30	8
	(2) Doppler/Computer		
	Program inactive stage of computer	20-60	8
	Determine present DR pos.	2-10	11
	Pilot present DR pos.	20	11
	Determine rho-theta data manual/tables	10-60	11
	Alter to new course	8-15	8
	Reprogram inactive stage of computer	20-60	8
	Ave - (1)	185 sec	
	(2)	225 sec	
	Max - (1)	280 sec	
	(2)	325 sec	
	Min - (1)	120 sec	
	(2)	150 sec	
	Pilot/Copilot		31 6%
	Navigator		44 2%

Event	Task	Time	Utilization Factor
Navigation System Management in Transition zone * (Doppler/Computer or INS)	Program nav./computer		
	INS	42 ea	8
	Doppler	24.3-64 3	8
	Determine fix		
	Vortac	29-81.4	11
	2 or 3 LOPS loran	42.6-205	11
	2 or 3 LOPS ADF	120-134.3	11
	Plot fix		
	Vortac	30-60	11
	2 or 3 LOPS loran	20-90	11
	2 or 3 LOPS ADF	20-60	11
	Determine DR position and plot	20	11
	Determine along track error	10-30	11
	Determine across track error	30-60	11
	Reset distance along track	4.3	8
	Reset distance across track	4 3	8
	Determine course change	10-45	11
	Initiate course change	4 3	8
	Correlate hdg, drift and track set in auto coupled mode	7 4-10	3
	Determine track angle error	15	11
	Check eta way point	30-90	11
	Record	3-5	8
	Ave	745 sec	
	Max	1025	
	Min	466	
	Pilot/Copilot		34 4%
	Navigator		48.2%

*Oceanic/Continental Transition Zone

Event/Flight Phase	Task	Time (sec)	Utilization Factor
(Moving Map Display Navigation Management Event)			
Pre-Taxi and Taxi	Select FIX mode	2.1	8
	Select waypoint	8 6	8
	Slew pen	12 0	8
	Select OP mode	2.1	8
T/O and Enroute and Landing	Select waypoint	8.6	8
Unprogrammed Waypoint	Select nav. aid	8 6	8
	Select WP mode	2.1	8
	Slew pen	12.0	8
	Select GB waypoint	8.6	8
	Return to waypoint	8 6	8
	Ave	73.3	
	Pilot/Copilot		28 6%
	Navigator		40.0%

TABLE D-V
TYPICAL VFR A-G AND G-A COMMUNICATIONS

TYPICAL VFR A-G AND G-A COMMUNICATIONS

Flight Phase	Message No	Type of Comm	Actual Communication	System with Selective Call #Words	System with Selective Call Time Sec	Present System #Words	Present System Time Sec
TAXI IN AND OUT	1	G/A	ATIS	50	33 6	50	33 6
	2	A/G	Cleveland Ground Control this is Cessna November 6032 Bravo.	0	0	11	7 8
	3	G/A	November 6032 Bravo Cleveland Ground	0	0	8	5 8
	4	A/G	Cessna 6032 Bravo VFR Detroit Wayne	3	2 5	9	6 5
	5	G/A	November 6032 Bravo cleared to runway 21 left via taxi-ways Alpha and Bravo Contact tower one-one-niner-point-three when ready	20	13 8	26	17 7
	6	A/G	One-one-niner-point-three	5	3 9	5	3 9
	7	A/G	Detroit Ground this is Cessna 6032 Bravo Would like to go to General Aviation Terminal via taxiways Alpha and Charlie Hold short taxiway Charlie for Beaumont 451	22	15 1	32	21 7
	8	G/A	Roger	1	1 2	1	1,2
DEPARTURE	9	A/G	Cleveland Tower this is Cessna 6032 Bravo VFR Detroit ready to go	5	3 9	15	10 5
	10	G/A	November 6032 Bravo cleared for immediate takeoff Maintain runway heading Contact departure control one-two-three-point-seven	15	10 5	21	14 4
	11	A/G	One-two-three-point-seven	5	3 9	5	3 9
	12	A/G	Cleveland Departure Control this is Cessna 6032 Bravo just off Runway two-one No transponder	7	5 2	18	12,4
	13	G/A	November 6032 Bravo climb to and maintain three thousand Turn right heading two-seven-zero Radar contact	14	9 8	20	13,8
	14	A/G	Cessna 6032 Bravo level at three thousand	4	3 2	10	7,2
	15	G/A	Roger.	1	1,2	1	1 2
	16	G/A	November 6032 Bravo 20 miles west of field Radar services terminated, Frequency change approved Resume normal navigation.	14	9 8	20	13 8
	17	A/G	Roger	1	1 2	1	1,2
	18-21	G/A	November 6032 Bravo traffic Eleven o'clock West bound 3 miles Slow moving	36	24 3	60	40 2
	22-25	A/G	Negative contact	6	4 5	6	4 5
	26-29	G/A	November 6032 Bravo traffic no longer a factor	20	13 8	44	29,6

TABLE V (cont'd)

Flight Phase	Message No	Type of Comm	Actual Communication	System with Selective Call #Words	System with Selective Call Time Sec	Present System #Words	Present System Time Sec
ENROUTE	30	A G	Cleveland Center this is Cessna 6032 Bravo one-two-six-point-three	0	0	15	10 5
	31	G A	November 6032 Bravo Cleveland Center	0	0	8	5 8
	32	A/G	Cessna 6032 Bravo VFR Detroit Wayne level at six thousand five hundred twenty miles west of Cleveland Hopkins. Heading two-seven-zero Request traffic advisories	22	15 1	28	19 0
	33	G/A	November 6032 Bravo turn left heading heading one-eight-zero for radar identification	10	7 2	16	11,1
	34	A/G	One-eight-zero	3	2 5	3	2,5
	35	G/A	November 6032 Bravo Radar contact	2	1 9	8	5 8
	36	G/A	November 6032 Bravo twenty miles southeast of Detroit Wayne contact approach control one-two-three-point-seven.	14	9,8	20	13 8
	37	A/G	One-two-three-point-seven.	5	3 9	5	3,9
	38-40	G/A	November 6032 Bravo traffic Eleven o'clock Westbound three miles slow moving.	27	18 4	45	30 3
	41-43	A/G	Negative contact	6	4 5	6	4 5
	44-46	G/A	November 6032 Bravo traffic no longer a factor.	15	10 5	33	22,3
ARRIVAL	47		ATIS	50	33 6	50	33,6
	48	A/G	Detroit Approach Control this is Cessna 6032 Bravo	0	0	11	7,8
	49	G/A	November 6032 Bravo Detroit approach control.	0	0	9	6,5
	50	A/G	Cessna 6032 Bravo twenty miles South-east of field heading three-three-zero degrees level at six-thousand-five hundred Landing	16	11 1	22	15 1
	51	G/A	November 6032 Bravo turn right heading zero-six-zero degrees for identification	9	6 5	15	10 5
ARRIVAL	52	A/G	Zero-six-zero	3	2 5	3	2 5
	53	G/A	November 6032 Bravo Radar contact Resume navigation	4	3 2	10	7,2
	54	G/A	November 6032 Bravo five miles Southeast of field Contact tower one-one-niner-point-one.	12	8 5	18	12,4
	55	A/G	One-one-niner-point-one	5	3 9	5	3,9
	56-59	G/A	November 6032 Bravo traffic eleven o'clock Westbound three miles slow moving	36	24 3	60	40,2
	60-63	A/G	Negative contact	8	5 8	8	5 8
	64-67	G/A	November 6032 Bravo traffic no longer a factor.	20	13,8	44	29 6

TABLE D-VI
TYPICAL IFR A-G AND G-A COMMUNICATIONS

TABLE V (cont'd)

Flight Phase	Message No	Type of Comm	Actual Communication	System with Selective Call: *Words	System with Selective Call: Time Sec	Present System: *Words	Present System: Time Sec
LANDING	68	A/G	Detroit Tower this is Cessna 6032 Bravo 5 miles Southeast level at six-thousand-five-hundred Landing	11	7.8	20	13.8
	69	G/A	November 6032 Bravo Report left downwind runway two-one. Number four to land	10	7.2	16	11.1
	70	A/G	Roger	1	1.2	1	1.2
	71	A/G	Cessna 6032 Bravo Downwind runway two-one	4	3.2	10	7.2
	72	G/A	November 6032 Bravo number three to land following a Bosch Baron	8	5.8	14	9.8
	73	A/G	Cessna 6032 Bravo We have him	3	2.5	9	6.5
	74	G/A	Roger	1	1.2	1	1.2
	75	G/A	November 6032 Bravo cleared to land	3	2.5	9	6.5
	76	G/A	November 6032 Bravo turn off next taxiway Contact ground one-two-one-point-seven	11	7.8	17	11.8
	77	A/G	One-two-one-point-seven	5	3.9	5	3.9
					393.1		630.4

* Alpha underlined words would be eliminated in an automated system

TABLE VI
TYPICAL IFR A-G AND G-A COMMUNICATIONS

Flight Phase	Message No.	Type of Comm	Actual Communication	System with Selective Call: *Words	System with Selective Call: Time Sec	Present System: *Words	Present System: Time Sec
TAXI IN & OUT	1	G/A	ATIS Information	50	33.6	50	33.6
	2	A/G	New York Clearance Delivery this is Cessna 6032 Bravo, IFR Detroit Wayne	0	0	15	10.5
	3	G/A	November 6032 Bravo we have your clearance	4	3.2	10	7.2
	4	A/G	November 6032 Bravo ready to copy	3	2.6	9	6.5
	5	G/A	November 6032 Bravo cleared Detroit Wayne. Tannersville ten. Flight planned route Expect flight level one-eight-zero after Tannersville. Contact Departure Control one-one-niner-point-two Squack one-three-zero-zero.	29	19.7	35	23.7
TAXI IN & OUT (cont.)	6	A/G	Cessna 6032 Bravo cleared Detroit Wayne Tannersville ten. Flight planned route Expect flight level one-eight-zero after Tannersville Contact Departure Control one-one-nine-point-two Squack one-three-zero-zero	29	19.7	35	23.7
	7	G/A	November 6032 Bravo your clearance is correct as read	6	4.7	12	8.5
	8	A/G	New York Ground Control this is Cessna 6032 Bravo	0	0	12	8.5
	9	G/A	November 6032 Bravo New York Ground	0	0	9	6.5
	10	A/G	Cessna 6032 Bravo with clearance IFR Detroit Wayne	5	3.9	11	7.9
	11	G/A	November 6032 Bravo cleared to runway 21 via taxiway Alpha Advise tower that you are an IFR Departure	16	11.2	22	15.1
	12	A/G	Detroit Ground Control this is Cessna 6032 Bravo Would like to taxi to hangar four	7	5.2	18	12.5
	13	G/A	November 6032 Bravo cleared hangar four via taxiway Alpha and Charlie	8	5.9	14	9.8
	14	A/G	Roger	1	1.3	1	1.26
DEPARTURE	15	A/G	New York tower this is Cessna 6032 Bravo New York Tower	0	0	9	6.5
	16	G/A	November 6032 Bravo New York Tower	0	0	9	6.5
	17	A/G	Cessna 6032 Bravo ready to go				
	18	G/A	November 6032 Bravo cleared for take-off Make SID Departure Contact Departure Control one-two-one-point-five	14	9.8	20	13.8
DEPARTURE (cont.)	19	A/G	Cessna 6032 Bravo rolling *	1	1.3	7	5.2
	20	A/G	Departure Control this is Cessna 6032 Bravo.	0	0	10	7.2
	21	G/A	November 6032 Bravo Departure Control. Squack Ident Radar Contact Climb to and maintain two thousand feet Maintain heading one-six-zero	16	11.2	24	16.4
	22	A/G	Cessna 6032 Bravo level at two thousand heading one-six-zero	8	5.9	14	9.8
	23	G/A	November 6032 Bravo climb to and maintain four thousand feet Turn right heading one-eight-zero Resume flight planned route at west texas	20	13.8	26	17.8
	24	A/G	Cessna 6032 Bravo out of two for four thousand. Right heading one-eight zero	11	7.9	17	11.8
	25	A/G	Cessna 6032 Bravo level at four Heading one-eight-zero	7	5.22	13	9.2
	26-31	G/A	November 6032 Bravo traffic eleven o'clock three miles. West bound slow moving.	9	6.5	15	10.5
	32-38	A/G	Negative Contact	2	1.9	2	1.9
	39-44	G/A	November 6032 Bravo traffic no longer a factor.	5	3.9	11	7.9
	45	G/A	November 6032 Bravo over West Texas VOR Contact New York Center one-one-niner-point-zero-five	14	9.8	20	13.8

TABLE D-VI (cont'd)
TYPICAL IFR A-G AND G-A COMMUNICATIONS

Flight Phase	Message No	Type of Comm	TABLE VI (cont'd) Actual Communication	System with Selective Call: Words	System with Selective Call: Time Sec.	Present System: Words	Present System: Time Sec
ENROUTE	46	A/G	New York Center this is Cessna 6032 Bravo one-one-niner-point-zero	0	0	16	11 2
	47	G/A	November 6032 Bravo this is New York Center Change to code one-zero-niner-zero Squack ident Radar contact.	11	7 9	22	15 1
ENROUTE (cont)	48	G/A	November 6032 Bravo contact New* York center one-two-three-point-five-five	10	7 2	16	11 2
	49	A/G	One-two-three-point-five-five	6	4 6	6	4 6
	50	A/G	New York center this is Cessna 6032 Bravo level at Flight-level one-eight-zero over Salem at fifteen estimate Bridgewater twenty-two Litchfield next	18	12,5	29	19 7
	51	G/A	Roger 6032 Bravo	1	1,3	6	4 6
	52	A/G	New York center this is Cessna 6032 Bravo one-two-three-point-five-five	0	0	16	11 2
	53	G/A	November 6032 Bravo Squack ident Radar contact.	4	3 2	10	7 2
	54	G/A	November 6032 Bravo contact Cleveland center one-two-six-point-five-five.	9	6,5	15	10 5
	55	A/G	One-two-six-point-five-five	6	4 6	6	4 6
	56	A/G	Cleveland center this Cessna 6032 Bravo one-two-six-point-five-five	6	4 6	16	11 2
	57	G/A	November 6032 Bravo Cleveland Center Change code to zero-one-seven-two Squack ident Radar contact	11	7,9	19	13 1
	58	G/A	November 6032 Bravo change frequency one-two-seven-point-nine-five	8	5 9	14	9 4
	59	A/G	One-two-seven-point-nine-five				
	60	A/G	Cleveland Center this is Cessna 6032 Bravo one-two-seven-point-five	0	0	16	11 2
	61	G/A	November 6032 Bravo Squack ident Radar contact.	6	4 6	10	7,2
	62	G/A	November 6032 Bravo descent to and maintain niner thousand Report leaving fourteen and sixteen thousand Current altimeter three-zero-point-zero-one.	18	12 5	24	16 4
	63	A/G	Cessna 6032 Bravo out of flight level* one-eight-zero for niner thousand	6	4 6	16	11, 2
	64	G/A	Roger	1	1 3	1	1,3
	65	A/G	Cessna 6032 Bravo passing thru four-teen thousand feet	5	3 9	11	7 9
	66	G/A	Roger	1	1 3	1	1 3
	67	A/G	Cessna 6032 Bravo passing three twelve thousand feet	5	3 9	11	7 9

* Alpha underlined words would be eliminated in an automated system

Flight Phase	Message No	Type of Comm.	TABLE VI (cont'd) Actual Communication	System with Selective Call: Words	System with Selective Call: Time Sec	Present System: Words	Present System: Time
ENROUTE (cont)	68	G/A	Roger	1	1 3	1	1 3
	69	A/G	November 6032 Bravo level at niner thousand	4	3 2	10	7 2
	70	G/A	Roger	1	1 3	1	1 3
	71	G/A	November 6032 Bravo contact Detroit approach control one-two-six-point-five-five	10	7 2	16	11 2
	72	A/G	One-two-six-point-five-five	6	4 6	6	4 6
	73-76	G/A	November 6032 Bravo traffic eleven o'clock west bound 3 miles slow moving	36	24 4	60	40,2
	77-80	A/G	Negative Contact	8	5,9	8	5 9
	81-84	G/A	November 6032 Bravo traffic no longer a factor.	20	13 8	44	29,6
ARRIVAL	85	A/G	Detroit approach control this is Cessna 6032 Bravo one-two-six-point-five-five level at niner thousand	4	3 2	21	14,5
	86	G/A	November 6032 Bravo change code to zero-one-zero-zero Squack ident Radar Contact	11	7,9	17	11 8
	87	G/A	November 6032 Bravo enter a holding pattern on the one-two-seven degree radial Salem VOR Turns Right Maintain niner-thousand.	18	12,5	24	16 4
	88	A/G	Cessna 6032 Bravo one-two-seven degree radial Salem VOR. Turns Right Niner thousand	11	7 9	17	11,8
ARRIVAL (cont)	89	G/A	November 6032 Bravo descend to and* maintain seven thousand Report passing eight thousand	10	7 2	16	11 3
	90	A/G	Cessna 6032 Bravo out of niner for seven	5	3 9	11	7,9
	91	A/G	Cessna 6032 Bravo passing thru eight thousand	4	3 2	10	7,2
	92	G/A	Roger	1	1 3	1	1 3
	93	A/G	Cessna 6032 Bravo level at seven thousand	4	3 2	10	7,2
	94	G, A	Roger	1	1 3	1	1,3
	95	G/A	November 6032 Bravo descend to and maintain five thousand feet. Report leaving six thousand	11	7 9	17	11 8
	96	A/G	Cessna 6032 Bravo out of seven four five	5	3 9	11	7,9
	97	A/G	Cessna 6032 Bravo passing thru six	3	2,6	9	6 5
	98	G/A	Roger	1	1 3	1	1 3
	99	A/G	Cessna 6032 Bravo level at five thousand	4	3 2	10	7 2
	100	G/A	Roger	1	1 3	1	1,3
	101	G/A	November 6032 Bravo descend to and maintain three thousand. Report leaving four thousand Expect clearance runway two-one at zero-seven-three-five	20	13 8	26	17 8

TABLE D-VI (cont'd)
TYPICAL IFR A-G AND G-A COMMUNICATIONS

Flight Phase	Message No	Type of Comm	TABLE VI (cont'd) Actual Communication	System with Selective Call		Present System	
				#Words	Time Sec	#Words	Time Sec
	102	A/G	Cessna 6032 Bravo out of five for three	5	3 9	11	7.9
	103	A/G	Cessna 6032 Bravo passing thru four	3	2.6	9	6 5
	104	G/A	Roger	1	1.3	1	1.3
	105	A/G	Cessna 6032 Bravo level at three	3	2 6	9	6 5
	106	G/A	November 6032 Bravo turn right heading one-eight-zero	6	4 6	12	8.5
ARRIVAL (cont)	107	A/G	One-eight-zero *	3	2.6	3	2 6
	108	G/A	November 6032 Bravo turn right heading two-five-zero.	6	4 6	12	8 5
	109	A/G	Two-five-zero	3	2 6	3	2 9
	110	G/A	November 6032 Bravo turn left heading two-four-zero. Intercept ILS Report tower p mile from outer marker inbound Contact tower one-one-niner-point-three	22	15 1	28	19.1
	111	A/G	Two-four-zero one-one-niner-point-three	6	4 6	6	4 7
APPROACH AND LAND	112		ATIS	50	33 6	50	33 6
	113	A/G	Detroit tower this is Cessna 6032 Bravo inbound over the outer marker	5	3 9	15	10 5
	114	G/A	November 6032 Bravo you are number two to land following a convair	9	6 5	15	10.5
	115	A/G	Roger	1	1 3	1	1 3
	116	G/A	November 6032 Bravo cleared to land	3	2 6	9	6 5
	117	G/A	November 6032 Bravo contact ground control one-two-one-point-seven.	8	5.9	14	9 8
	118	A/G	One-two-one-point-seven	5	3 9	5	3 9

* alpha underlined words would be eliminated in an automated system

pilot in the control and monitor of his vehicle is possible. Communication and navigation management workload is assessed independently of the control and monitor workload.

D.4.1 VTOL Aircraft

A time line analysis for VTOL aircraft is shown in Table D-VII. Pilot and copilot tasks of a lift fan VTOL include the manual vehicle control and visual monitor tasks.

D.4.2 STOL Aircraft

Table D-VIII summarizes a typical set of control and monitor tasks for a STOL aircraft. The vehicle selected for evaluation was a turbofan STOL operated over a 500 nmi stage length.

TABLE D-VII
VTOL LIFT FAN PILOT AND COPILOT WORKLOAD

VTOL LIFT FAN PILOT AND COPILOT WORKLOAD

Phase	Time	Pilot Visual Task: Start Time	Pilot Visual Task: Task	Pilot Visual Task: Duration	Pilot Manual Task: Start Time	Pilot Manual Task: Task	Pilot Manual Task: Duration
Pre-Taxi	-12.0				-11.7	Brakes set	0.1
		-11.6	A/C Configuration	0.3			
		-11.3	CHK Thrust Det Pos	0.1			
					-11.2	Ground Control	0.3
					-10.9	Intercomm	0.3
		-10.3	Fuel Mgmt	0.1			
		-10.2	Alt. airspeed	0.2	-10.2	Set Alt. airspeed Indicator	0.2
		-10.0	Roll-Pitch-Yaw Trim	0.2	-10.0	Set Roll-Pitch-Yaw Trim	0.2
		- 9.4	Alt. Hdg. Inds	0.1			
					- 9.3	Turbine on Start	0.1
					- 9.2	No. 1 Engine Start	0.2
					- 9.0	No. 2 Engine Start	0.2
					- 8.8	No. 3 Engine Start	0.2
					- 8.6	No. 4 Engine Start	0.2
					- 7.7	Adj Cont Auth	0.1
					- 7.6	Chk Flt Controls	0.1
					- 7.5	Engage Automatic Stabilization Equipment	0.1
		- 7.4	Cyc WG Position Control	0.3	- 7.4	Cyc WG Position Control	0.3
		- 7.1	Pre-taxi Chk List Complete	1.0	- 7.1	Pre-taxi Chk List Complete	1.0
Taxi	- 6.1	- 6.1	Scan Taxiway	0.2	- 6.1	Taxi to Position, Control	0.2
Pre-Take-Off	- 5.9				- 5.9	Fuel Chk out	0.2
		- 5.7	Monitor Heading	0.1			
					- 5.6	Set Brakes	0.1
		- 5.5	Eng No. 1 Instruments	0.4	- 5.5	Eng No. 1 Chk out	0.4
		- 5.1	Eng No. 2 Instruments	0.4	- 5.1	Eng. No. 2 Chk out	0.4
		- 4.7	Eng No. 3 Instruments	0.4	- 4.7	Eng. No. 3 Chk out	0.4
		- 4.3	Eng No 4 Instruments	0.4	- 4.3	Eng No. 4 Chk out	0.4
Taxi	- 3.8	- 3.8	Scan Taxiway	1.0	- 3.8	Taxi to Spot	1.0
					- 2.9	Eng RPM to 60%	0.2
					- 2.3	No. 1 Eng Div Valve to Fan	0.1
		- 2.2	Monitor Fan RPM-Temp, Engine Instruments	0.7			
					- 2.1	No. 1 Div Valve to Norm	0.1
					- 2.0	No. 2 Div Valve to Fan	0.1
					- 1.9	No. 2 Div Valve to Norm	0.1
					- 1.8	No. 3 Eng Div Valve to Fan	0.1
					- 1.7	No. 3 Div Valve to Norm	0.1
					- 1.6	No. 4 Eng Div Valve to Fan	0.1
					- 1.5	No. 4 Div Valve to Norm	0.1
		- 0.5	Monitor Engine Instruments	0.2	- 0.5	Engs to 60%	0.2
					- 0.3	All Div Valves to Fan	0.2
		- 0.2	CHK Fan RPM	0.1			
		- 0.1	CHK Eng Instruments	0.1			
Take Off	0.0				0.0	Throttles to Take-off Power	0.2
		0.2	CHK Thrust Req-Avail	0.1			
		0.3	Lift Off Scan	0.5	0.3	Lift Off Throttle	0.5
		0.8	Monitor Attitude, Heading, Altitude	1.9	0.8	Control Attitude, Heading	1.9
		2.4	Monitor Thrust	0.1	2.4	Adj Thrust	0.1
Clear to 1000 ft MOCA	2.5	2.5	Flight Instrument Scan (5 sec every 20 sec)	2.0	2.5	Increase Along Track Airspeed, Altitude	0.1
					2.6	Attain WG Lift, Angle of Attack	0.1
Conversion	2.7				2.7	Div 2 Eng Aft	0.2
		2.8	CHK Div Pos	0.4			
					2.9	Div 3 Eng Aft	0.2
					3.1	Increase Airspeed, Altitude	0.2
					3.3	Div 1 Eng Aft	0.2

TABLE D-VII (cont'd)
VTOL LIFT FAN PILOT AND COPILOT WORKLOAD

VTOL LIFT FAN PILOT AND COPILOT WORKLOAD

Phase	Time	Pilot Visual Task: Start Time	Task	Duration	Pilot Manual Task: Start Time	Task	Duration
					3.5	Div 4 Eng Aft	0.2
					3.7	Adj Climb Thrust	0.1
					3.8	Maint Climb A/A-Att	0.2
Acc. to Climb	3.9						
		4.0	Monitor Climb A/A-Attitude	0.2			
		4.2	Autopilot	3s	4.2	Engage Autopilot	3s
		4.2	Monitor Eng Inst, Flight Instrument (scan)	0.1			
					9.5	Attain Cruise Altitude	0.1
					9.6	Attain Cruise Speed	0.1
Cruise	9.7				9.7	Reduce Throttle	0.1
		9.8	Scan Flight Instruments and Engine Instruments (5 sec every 20 sec)	10.5	9.8	Engage Autopilot	0.1
		9.9	Monitor Autopilot Hold mode	0.1			
					10.0	Throttle	0.2
		10.2	Flight Inst., Engine Inst., Cockpit	0.2	10.2	Cruise Check	0.5
		30.2	Monitor Mach Meter, Engine Inst.	0.1	30.2	Throttle	0.1
Descent	52.3	52.3	Scan Flight Inst., Engine Inst. (5 sec every 20 sec)	4.0	52.3	Reduce Thrust as Req	0.1
		52.4	Pitch Thumbwheel	0.1	52.4	Pitch Thumbwheel for Desired ROD	0.1
		52.5	Flt. Inst., Mach Meter, IAS	0.1	52.5	Throttle	0.1
					54.5	Throttle	0.1
		54.6	Flt. Inst., Mach Meter, IAS	0.1	54.6	Set Altimeter	0.1
		54.7	Altimeter	0.1			
		57.7	Flt. Inst. Mach Meter, IAS	0.1	57.7	Throttle	0.1
Terminal Area	57.8	57.8	Pitch Thumbwheel	0.1	57.8	Pitch Thumbwheel for Desired ROD	0.1
		57.9	Flt. Inst., Mach Meter, IAS	0.1	57.9	Throttle	0.1
Conversion	63.1				63.1	Speed Brakes On	0.1
					63.2	Slow to App Speed	2.6
					65.8	Throttle Conversion Speed	0.1
		65.9	Divert Eng to Fans	0.3	65.9	Divert Eng to Fans	0.3
		66.2	CHK Fan RPM-temp	0.5	66.2	Descend to Conversion Altitude	0.5
		66.7	Complete Conversion	0.2	66.7	Complete Conversion	0.2
					66.9	Increase Throttle	0.1
		67.9	Monitor Hover Indicator	0.1			
Land	68.0	68.0	Land	0.1	68.0	Land	0.1
					68.7	Thrust to-Idle	0.1
					68.9	Both Diverter Valves to Rear	0.1
		70.0	Taxi to Park Area	1.5	70.0	Taxi to Park Area	1.5

TABLE D-VII (cont'd)
VTOL LIFT FAN PILOT AND COPILOT WORKLOAD

VTOL LIFT FAN PILOT AND COPILOT WORKLOAD

Phase	Time	Co-Pilot Visual Task			Co-Pilot Manual Task		
		Start Time	Task	Duration	Start Time	Task	Duration
Pre-taxi	-12.0						
					-11.6	Radio Master On	0.1
		-10.6	Lights	0 1	-10.6	CHK Warn Lights	0.1
		-10.5	CHK Fire Warn Sys Off	0.1			
		-10.4	CHK Comm-Nav Insts	0.1	-10.4	CHK Comm-Nav Insts	0.1
		-10.2	Altitude, airspeed	0.2	-10.2	Set Altitude, Airspeed	0.2
		- 9.7	CHK Anti-ice	0.2			
		- 9.3	Attitude - Heading Indicators	0.1			
					- 8.7	Batt-Gen On	0.1
		- 8.2	Monitor Fuel Mgmt System	0.3			
		- 7.6	CHK Hydraulic System	0.1	- 7.6	CHK Hydraulic System	0 1
Taxi	- 6.1						
Pre-Take-Off	- 5.9						
Taxi	- 3.8						
					- 2.7	All Louver Doors Open	0.2
		- 2.4	CHK Louver Door Inds	0.1			
					- 1.4	Set WG to Take Off Position	0.2
		- 1.2	WG Position Indicator	0.1			
		- 1.0	Fuel Controls	0.3	- 1.0	CHK Fuel Controls	0.3
Take Off	0.0						
		0.07	Electronics Panel	2s	0.07	Switch from Tower to Dep. Control	2s
		0.3	Gear Position Indicators	0.1	0.2	Gear Up Handle	0.1
		0.4	Electronics Panel	2s	0.4	Switch Landing Beam to VOR Freq	2s
		0.44	Electronics Panel	8.6s	0.44	Select Nav. Freq.	8.6s
		0.59	Electronics Panel	8.6s	0.59	Select Comm. Freq	8.6s
		0.73	Scan Flight Inst. and Engine Inst. (5 sec every 20 sec)	2.3			
Conversion	2.7						
		2.8	Close Louver Doors	0.1	2.8	Close Louver Doors	0 1
		2.9	CHK Louver Door Indicators	0.1			
		3.8	Flight Inst., Engine Inst. Cockpit	30s	3.8	Climb Check	0.5
		6.0	Altimeter	5s	6.0	Set Altimeter 29.92	0 1
		7.0	Electronics Panel	2s	7.0	Switch to Next Comm. Freq.	2s
		7.03	Electronics Panel	8.6s	7.03	Select Comm. Freq.	8.6s
					9.3	Notify Pilot 1000 ft. to Cruising Altitude	1s
					9.5	Switch to Ext Fuel	0.1
		9.6	Set WG Pos to Hi-Alt Cruise	0.1	9.6	Set WG Pos. to Hi-Alt Cruise	0.1
Cruise	9.7						
		9.8	Scan Flight Inst. and Engine Inst. (5 sec every 20 sec)	10.5			
		10.2	Flight Inst., Engine Inst., Cockpit	0.5	10.2	Cruise Check	0.5
		10.75	Electronics Panel	2s	10.75	Switch to Nex. Nav. Freq.	2s
		10.77	Electronics Panel	8.6s			
					10.78	Select Next Nav Freq.	8.6s
		25.0	Electronics Panel	2s	25.0	Switch to Next Comm Freq	2s
		25.03	Electronics Panel	8.6s	25.03	Select Comm. Freq.	8.6s
		45.0	Electronics Panel	2s	45.0	Switch to Next Nav. Freq.	2s
		45.03	Electronics Panel	8.6s	45.03	Select Next Nav. Freq.	8.6s
		50.0	Fuel Gauges, Writing Board	10s	50.0	Fill Out Fuel Sheet	10s
		50.1	Electronics Panel	2s	50.1	Switch to Next Comm. Freq.	2s
		50.13	Electronics Panel	8.6s	50.13	Select Next Comm. Freq.	8.6s
		51.0	Electronics Panel	8.6s	51.0	Select Appraoch Control Freq.	8.6s
		51.15	Electronics Panel	2s	51.15	Switch to Next Nav. Freq.	2s

D.4.3 SST Aircraft

Table D-IX presents typical SST pilot and copilot control and monitor tasks. The workload is evaluated with respect to a 3,400 nmi transoceanic mission. Workload was estimated to be minimal as a consequence of the extensive use of automation.

D.4.4 CTOL Aircraft

Table D-X presents the results of an analysis of the visual and manual workload experienced by the pilot and copilot of a CTOL class of aircraft. The analysis was done for a 4-engine jet transport. A three-man crew was assumed - the third member being the flight engineer. The long haul mission profile is shown in Sec. 2, Vol. II.

D.4.5 GA2 Aircraft

Table D-XI lists pilot and copilot control/monitor tasks for a GA2 type of aircraft. The analysis was done for a single engine, constant speed propeller, retractible gear aircraft operating on a VFR flight plan. The mission profile of 190 minutes is taken as representative. The manual and visual workload experienced by the pilots of a twin-engined aircraft is estimated to be only slightly greater; thus the workload figures for the selected aircraft were assumed to be an adequate approximation of the workload figures for any GA2 vehicle.

While the GA1 class of aircraft is theoretically less difficult to fly and to navigate than is the GA2 class of aircraft, most GA1 pilots have fewer total flying hours per year and generally operate as one-man crews; thus, the demands on the GA1 pilot will probably be as great or greater than is the case for the GA2.

This relative lack of experience on the part of the pilot flying GA1 aircraft means that he will probably be just as busy as a GA2 pilot; thus the workloading analysis for a GA2 aircraft is a reasonable approximation of the workloading for a GA1 aircraft.

TABLE D-VIII
STOL TURBOFAN PILOT AND COPILOT WORKLOAD

TABLE VII (cont'd)
VTOL LIFT FAN PILOT AND COPILOT WORKLOAD

Phase	Time	Co-Pilot Visual Task: Start Time	Task	Duration	Co-Pilot Manual Task: Start Time	Task	Duration
Cruise (cont.)		51.30	Electronics Panel	8.6s	51.30	Select Landing Freq.	8.6s
					52.1	Change to Int Fuel	0.1
		52.2	Fuel Pressure	0.1			
Descent	52.3	52.3	Scan Flight Inst., Engine Inst. (5 sec every 20 sec)	1.3			
		52.5	Altimeter	5s	52.5	Set and Cross-check Altimeter	5s
		62.0	Flight Inst., Engine Inst., Cockpit	1	62.0	In-Range Check	1
Conversion	63.1	63.1	WG Position for Landing	0.3	63.1	Set WG Position for Landing	0.3
					65.7	Flaps Down	0.1
		65.8	Flap Indicator	0.1			
		66.2	Electronics Panel	2s	66.2	Switch to Landing Freq.	2s
		66.7	Gear Handle	3s	66.7	Gear Down	3s
		66.8	Flight Inst., Engine Inst., Cockpit, Writing Board	20s	66.8	Landing Check	20s
Land	68.0	68.0	Electronics Panel	2s	68.0	Switch to Tower Freq.	2s
		68.1	Electronics Panel	8.6s	68.1	Select Ground Control Freq.	8.6s
					68.2	Call Out Threshold and Final Approach Speed	2s
		68.3	Monitor Engine Inst. and Watch for Pad	0.5			
Taxi	70.0	70.0	CHK Valve Position	0.1			
		70.2	CHK Louver Door Indicator	0.2			
					70.6	Close Louver Doors	0.1
		70.7	Electronics Panel	2s	70.7	Switch to Ground Control	2s
		70.8	Thrust Control	2s	70.8	Thrust Control - Forward Idle	2s
		71.5	Cockpit	1	71.5	Shut Down Check List	1

TABLE VIII
STOL TURBOFAN PILOT AND COPILOT WORKLOAD

Phase	Pilot Visual Task: Start Time	Task	Duration	Pilot Manual Task: Start Time	Task	Duration
Take-Off and Departure				-0.44	Hold Brakes	10s
				-0.41	Call for Flaps 25°	1s
	-0.40	Engine Instruments	10s	-0.40	Advance Throttles	2s
	-0.27	Scan Runway	16s	-0.27	Release Brakes	1s
				-0.27	Control Column, Rudder, Throttles	2.0
				-0.15	Acknowledge V_1	1s
	0.00	Flight Instruments	1.5	0.00	Acknowledge V_R, Rotate	3s
				0.08	Call for Gear Up (Right Hand Thumb Up)	1s
				0.18	Call for Flaps - 10°	1s
Clear to 1000 ft MOCA	0.30	Engine Instruments	3s	0.30	Reduce Power to Climb Setting	3s
				0.31	Call for Flap Retraction	1s
	1.5	Autopilot	3s	1.5	Engage Auto Pilot	3s
	1.55	Pitch Thumb Wheel & Flight Inst.	10s	1.55	Adjust Pitch Thumb Wheel for Desired ROC	10s
	1.72	Scan Flight Inst. & Engine Instruments (5 sec) every 20 sec.	2.8			
	1.72	Flight Inst., Engine Inst., Cockpit	0.5	1.72	Climb Check	0.5
	6.00	Altimeter	5s	6.00	Set Altimeter 29.92	5s
				12.20	Acknowledge 1000 Feet to Cruising Altitude	1s
	12.22	Pitch Thumbwheel		12.22	Adjust Pitch Thumbwheel for Zero ROC	10s

TABLE D-VIII (cont'd)
STOL TURBOFAN PILOT AND COPILOT WORKLOAD

TABLE VIII (cont'd)
STOL TURBOFAN PILOT AND COPILOT WORKLOAD

Phase	Pilot Visual Task: Start Time	Pilot Visual Task: Task	Pilot Visual Task: Duration	Pilot Manual Task: Start Time	Pilot Manual Task: Task	Pilot Manual Task: Duration
	12.85	Flight Inst., Engine Inst., Cockpit	15s	12.85	Cruise Check	0.5
	37.0	Monitor Mach. Meter, Engine Inst.	10s	37.0	Throttle	10s
Descent & Landing	64.2	Scan Flight Inst. & Engine Inst. (5 sec) every 20 sec.	5	64.2	Advise Crew of Descent	2s
	64.23	Engine Instruments	3s	64.23	Throttle	3s
	64.7	Pitch Thumbwheel	10s	64.7	Adjust Pitch Thumbwheel for Desired ROD	10s
	64.9	Flight Inst., Mach. Meter, IAS	10s	64.9	Adjust Throttle	10s
	66.9	Flight Inst., Mach. Meter, IAS	10s	66.9	Adjust Throttle	10s
	67.1	Altimeter	5s	67.1	Set & Cross-check Altimeters	5s
Terminal Area	70.8	Flight Inst., Mach. Meter, IAS	10s	70.8	Adjust Throttle	10s
	70.9	Pitch Thumbwheel	0.1	70.9	Pitch Thumbwheel for Desired ROD	0.1
	71.0	Flight Inst., Mach. Meter, IAS	0.1	71.0	Throttle	0.1
	76.1	Flight Inst., Engine Inst., Cockpit	1	76.1	Call for In-Range Check	1s
				77.9	In-Range Check	1
Approach 78.9	79.4	Monitor Airspeed	2s	79.4	Call for Flaps 15°	1s
	79.5	RMI	5s	79.5	Move Hdg. Bug to Required Heading	0.1
	80.5	Auto Pilot	3s	80.5	Auto Pilot - Hdg. Sel.	0.1
	80.6	Monitor Airspeed	2s	80.6	Call for Flaps 25°	1s
Final Approach	81.9	Auto Pilot	0.1	81.9	Auto Pilot - Turn	0.1
	82.0	Turn Knob	0.1	82.0	Turn Knob	0.1
	82.1	Monitor Airspeed	2s	82.1	Call for Gear Down	1s
	82.5	Auto Pilot	3s	82.5	Auto Pilot - Land	0.1
	82.6	Monitor Airspeed	2s	82.6	Call for Flaps 35°	1s
	82.6	Flight Inst., Engine Inst., Cockpit	20s	82.6	Landing Check	0.3
	82.7	Monitor Airspeed	2s	82.8	Hand on Throttle	1.3
	82.8	Monitor Flight Inst.	2.25	82.8	Call for Full Flaps	1s
				83.5	Repeat Threshold & Final Approach Speed	2s
	83.6	Approach Lights & Runway	45s	83.6	Auto Pilot - Disengage	1s
				83.6	Control Wheel, Rudder	
				83.6	Throttle Back	2s
Land	83.8			83.8	Call - Buckets	1s
				83.8	Brakes	0.3
Taxi	84.1	Taxi Way		84.1	Rudders & Brakes, Throttle	3m
	87.1	Cockpit		87.1	Shut Down Check List	1m

TABLE D-VIII (cont'd)
STOL TURBOFAN PILOT AND COPILOT WORKLOAD

TABLE VIII (cont'd)
STOL TURBOFAN PILOT AND COPILOT WORKLOAD

Phase	Copilot Visual Task			Copilot Manual Task		
	Start Time	Task	Duration	Start Time	Task	Duration
Departure	-0.27	Monitor IAS, Engine Inst., Flight Inst.	0.5	-0.41	Flap Handle 25°	3s
				-0.17	Notify Pilot V_1	1s
				-0.02	Notify Pilot V_R	1s
	0.07	Electronics Panel	2s	0.07	Switch from Tower to Dep. Cont.	2s
	0.10	Gear Handle	3s	0.10	Gear Up Handle	3s
	0.20	Gear Position Indicator & Flap Handle	3s	0.20	Flap Handle 10°	3s
	0.33	Flap Handle	3s	0.33	Flap Handle 0°	3s
	0.38	Electronics Panel	2s	0.38	Switch from	2s
	0.41	Electrical Switch	2s	0.41	Seat Belt-Smoking Switch	2s
	0.44	Electronics Panel	8.6s	0.44	Select Nav. Freq.	8.6s
	0.59	Electronics Panel	8.6s	0.59	Select Comm. Freq.	8.6s
	0.73	Scan Flight Inst. & Engine Inst. (5 sec) every 20 sec.	2.9			
	1.72	Flight Inst., Engine Inst. Cockpit	0.5	1.72	Climb Check	30s
	6.00	Altimeter	5s	6.00	Set Altimeter 29.92	5s
	7.00	Electronics Panel	2s	7.00	Switch to Next Comm. Freq.	2s
	7.03	Electronics Panel	8.6s	7.03	Select Comm. Freq.	8.6s
				12.18	Notify Pilot 1000 Feet to Cruising Altitude	1s
	12.22	Scan Flight Inst. & Engine Inst. (5 sec) every 20 sec.	12.9			
	12.85	Flight Inst., Engine Inst., Cockpit	0.5	12.85	Cruise Check	0.5
	13.35	Electronics Panel	2s	13.35	Switch to Next Nav. Freq.	2s
	13.38	Electronics Panel	8.6s	13.38	Select Next Nav. Freq.	8.6s
	29.0	Electronics Panel	2s	29.0	Switch to Next Comm. Freq.	2s
	29.03	Electronics Panel	8.6s	29.03	Select Comm. Freq.	8.6s
	37.00	Electronics Panel	2s	37.00	Switch to Next Nav.Freq.	2s
	37.03	Electronics Panel	8.6s	37.03	Select Next Nav. Freq.	8.6s
	38.0	Fuel Gages, Writing Board	10s	38.0	Fill Out Fuel Sheet	10s
	52.00	Electronics Panel	2s	52.00	Switch to Next Comm.Freq	2s
	52.03	Electronics Panel	8.6s	52.03	Select Next Comm. Freq.	8.6s
	52.17	Electronics Panel	2s	52.17	Switch to Next Nav.Freq.	2s
	52.20	Electronics Panel	8.6s	52.20	Select Next Nav. Freq.	8.6s
	58.50	Electronics Panel	2s	58.50	Switch to Next Comm.Freq	2s
	58.53	Electronics Panel	8.6s	58.53	Select Approach Control Freq	8.6s
	58.67	Electronics Panel	2s	58.67	Switch to Next Nav.Freq.	2s
	58.70	Electronics Panel	8.6s	58.70	Select Landing Freq.	8.6s
Descent	64.2	Scan Flight Inst., Engine Inst. (5 sec) every 20 sec	5			
	67.1	Altimeter	5s	67.1	Set & Cross-check Altimeter	5s
	76.1	Flight Inst., Engine Inst., Cockpit	1	76.1	In-Range Check	1
	79.4	Flap Handle	3s	79.4	Flap Handle 15°	3s
	80.7	Flap Handle	3s	80.7	Flap Handle 25°	3s
	81.8	Electronics Panel	2s	81.8	Switch to Landing Freq.	2s
	82.1	Gear Handle	3s	82.1	Gear Down	3s
	82.6	Flap Handle	3s	82.6	Flap Handle 35°	3s
	82.6	Flight Inst., Engine Inst., Cockpit, Writing Board	20s	82.6	Landing Check	20s

TABLE D-IX
SST PILOT AND COPILOT WORKLOAD

TABLE VIII (cont'd)
STOL TURBOFAN PILOT AND COPILOT WORKLOAD

Phase	Copilot Visual Task			Copilot Manual Task		
	Start Time	Task	Duration	Start Time	Task	Duration
	82.80	Flap Handle	3s	82.80	Flap Handle Full	3s
	82.85	Electronics Panel	2s	82.85	Switch to Tower Freq.	2s
	82.88	Electronics Panel	8.6s	82.88	Select Ground Control Freq.	8.6s
				83.5	Call Out Threshold & Final Approach Speed	2s
	83.0	Monitor Engine Inst. & Watch for Runway	1.25	83.55	Seat Belt & Smoking Switch	2s
				83.8	Throttle	45s
	83.80	Thrust Control	2s	83.80	Thrust Control - Reverse Idle	2s
	83.83	Engine Inst.	10s	83.83	Advance Throttles	10s
				83.96	Retard Throttles	3s
	84.0	Electronics Panel	2s	84.0	Switch to Ground Control	2s
	84.1	Thrust Control	2s	84.1	Thrust Control - Forward Idle	2s
Taxi	87.1	Cockpit	1	87.1	Shut Down Check List	1

TABLE IX
SST PILOT AND COPILOT WORKLOAD

PHASE	Pilot Visual Task			Pilot Manual Task		
	Start Time	Task	Duration	Start Time	Task	Duration
Take-Off, Climb and Accelerate				-0.66	Hold Brakes	10s
	-0.63	Engine Instruments	10s	-0.63	Advance Throttles	2s
	-0.50	Scan Runway	33s	-0.50	Release Brakes	1s
				-0.50	Control Column, Rudder, Throttles	1.5m
				-0.33	Acknowledge V_1	1s
	0.00	Flight Instruments	1.0m	0.00	Acknowledge V_R, Rotate	3s
				0.08	Call for Gear Up (Right Hand Thumb Up)	1s
				0.18	Call for Flaps - 10°	1s
	0.26	Engine Instruments	3s	0.26	Reduce Power to Climb Setting	3s
	1.00	AFCS	3s	1.00	Engage AFCS	3s
	1.05	AFCS	10s	1.05	Adjust AFCS	10s
	1.72	Scan Flight Inst. & Engine Instruments (5 sec) every 20 sec.	10.7m			
	1.72	Flight Inst., Engine Inst., Cockpit	30s	1.72	Climb Check	30s
	2.40	AFCS	10s	2.40	Adjust AFCS	10s
	5.50	Altimeter	5s	5.50	Set Altimeter 29.92	5s
	13.70	AFCS	10s	13.70	Adjust AFCS	10s
	29.95	AFCS	10s	29.95	Adjust AFCS	10s
	42.20	AFCS	10s	42.20	Adjust AFCS	10s
				44.20	Acknowledge Cruising Altitude	1s
	44.53	AFCS	10s	44.53	Adjust AFCS	10s

TABLE D-IX (cont'd)
SST PILOT AND COPILOT WORKLOAD

TABLE IX (cont'd)
PILOT AND COPILOT WORKLOAD

PHASE	Pilot Visual Task: Start Time	Task	Duration	Pilot Manual Task: Start Time	Task	Duration
Cruise	44.70	Scan Flight Instruments & Engine Inst. (5 sec) every 20 sec.	41.0m			
	44.70	Flight Inst, Engine Inst., Cockpit	15s	44.70	Cruise Check	30s
Decelerate, Descend and Land				208.67	Advise Crew of Descent	2s
	208.7	Scan Flight Inst. & Engine Inst. (5 sec) every 20 sec.	6.5m			
	208.7	AFCS	10s	208.7	Adjust AFCS	10s
	210.7	AFCS	10s	210.7	Adjust AFCS	10s
	223.57	Altimeter	5s	223.57	Set & Cross-check Altimeters	5s
				224.5	Call for In-Range Check	1s
	224.7	Flight Instrument, Engine Inst., Cockpit	1m	224.7	In-Range Check	1m
	227.49	RMI	5s	227.49	Move Heading Bug to Required Heading	5s
	227.57	AFCS	3s	227.57	Adjust AFCS	3s
	231.4	AFCS	3s	231.4	AFCS - Turn	3s
	231.45	Turn Knob	30s	231.45	Turn Knob	30s
	231.5	Flight Instrument, Engine Inst., Cockpit	20s	231.5	Landing Check	20s
	232.0	AFCS	3s	232.0	AFCS - ILS	3s
				232.2	Call for Gear Down	1s
	233.2	Monitor Flight Instrument	1.5m	233.2	Hand on Throttle	1.5m
				233.2	Repeat Threshold and Final Approach Speed	2s
	234.45	Approach Lights & Runway	45s			
				234.45	Disengage AFCS	1s
				234.45	Control Wheel, Rudder	45s
				234.45	Throttle Back	2s
				234.7	Touchdown	
				234.7	Call - Buckets	1s
				234.7	Brakes	18s
Taxi	235.2	Taxi Way		235.2	Steering Wheel, Brakes and Throttle	3m
	238.2	Cockpit		238.2	Shut Down Check List	1m

PHASE	Copilot Visual Task: Start Time	Task	Duration	Copilot Manual Task: Start Time	Task	Duration
Take-Off, Climb and Accelerate	-0.50	Monitor IAS, Engine Inst., Flight Inst.	33s			
				-0.35	Notify Pilot V_1	1s
				-0.02	Notify Pilot V_R	1s
	0.07	Electronics Panel	2s	0.07	Switch from Tower to Dep. Cont.	2s
	0.10	Gear Handle	3s	0.10	Gear Up Handle	3s
	0.41	Electrical Switch	2s	0.41	Seat Belt - Smoking Switch	2s
	0.59	Electronics Panel	8.6s	0.59	Select Comm. Frequency	8.6s
	0.73	Scan Flight Instrument & Engine Inst. (5 sec) every 20 sec.	11m			
	0.86	Electronics Panel	8.6s	0.86	Switch from ILS Frequency to Waypoint	8.6s
	1.72	Flight Inst., Engine Inst., Cockpit	30s	1.72	Climb Check	30s
	5.50	Altimeter	5s	5.50	Set Altimeter 29.92	5s

TABLE D-IX (cont'd)
SST PILOT AND COPILOT WORKLOAD

TABLE IX (cont'd)
SST PILOT AND COPILOT WORKLOAD

PHASE	Copilot Visual Task			Copilot Manual Task		
	Start Time	Task	Duration	Start Time	Task	Duration
Take-Off, Climb and Accelerate (Contd.)	6.00	Electronics Panel	2s	6.00	Switch to Next Comm. Freq.	2s
	6.03	Electronics Panel	8.6s	6.03	Select Comm. Frequency	8.6s
				44.00	Notify Pilot - Coming Up on Cruising Altitude	1s
	44.70	Scan Flight Inst. & Engine Inst. (5 sec) every 20 sec.	41m			
	44.70	Flight Inst., Engine Inst., Cockpit	30s	44.70	Cruise Check	30s
	45.50	Electronics Panel	8.6s	45.50	Switch to Next	8.6s
	46.04	Electronics Panel	2s	46.04	Switch to Next Comm. Frequency	2s
	46.07	Electronics Panel	8.6s	46.07	Select Comm Frequency	8 6s
	60.00	Fuel Gages, Writing Board	10s	60.00	Fill Out Fuel Sheet	10s
	78.07	Electronics Panel	8.6s	78.07	Switch to Next Waypoint	8.6s
	110.07	Electronics Panel	2s	110.07	Switch to Next Comm. Freq.	2s
	110.10	Electronics Panel	8.6s	110.10	Select Next Comm. Freq.	8.6s
	110.24	Electronics Panel	2s	110.24	Switch to Next Waypoint	8.6s
	120.00	Fuel Gages, Writing Board	10s	120.00	Fill Out Fuel Sheet	10s
	142.24	Electronics Panel	2s	142.24	Switch to Next Comm. Freq.	2s
	142.27	Electronics Panel	8.6s	142.27	Select Comm. Freq.	8.6s
	142.41	Electronics Panel	8.6s	142.41	Switch to Next Waypoint	8.6s
	175.00	Electronics Panel	2s	175.00	Switch to Next Comm. Freq.	2s
	175.03	Electronics Panel	8.6s	175.03	Select Approach Control Frequency	8.6s
	175.17	Electronics Panel	8.6s	175.17	Switch to Next Waypoint	8.6s
	180.00	Fuel Gages, Writing Board	10s	180.00	Fill Out Fuel Sheet	10s
	208.00	Electronics Panel	2s	208.00	Switch to Approach Control	2s
	208.03	Electronics Panel	8.6s	208.03	Select Tower Freq.	8.6s
	208.17	Electronics Panel	8.6s	208.17	Switch to Next Waypoint	8.6s
	208.31	Electronics Panel	8.6s	208.31	Select ILS Frequency	8.6s
Decelerate, Descend and Land	208.70	Scan Flight Inst., Engine Inst. (5 sec) every 20 sec	6.5m			
	223.57	Altimeter	5s	223.57	Set & Cross-check Altimeter	5s
	224.50	Flight Inst., Engine Inst., Cockpit	1m	224.50	In-Range Check	1m
	225.50	Electronics Panel	2s	225.50	Switch to ILS Frequency	2s
	231.50	Flight Inst., Engine Inst., Cockpit, Writing Board	20s	231.50	Landing Check	20s
	232.22	Gear Handle	3s	232.22	Gear Down	3s
	232.30	Electronics Panel	2s	232.30	Switch to Tower Freq.	2s
	232.35	Electronics Panel	8.6s	232.35	Select Ground Control Frequency	8 6s
				232.75	Seat Belt & Smoking Switch	2s
				232.90	Call Out Threshold and Final Approach Speed	2s
	233.20	Monitor Engine Inst. and Watch for Runway	1.5m			
				234.65	Throttle	45s
	234.70	Thrust Control	2s	234.70	Thrust Control - Reverse Idle	2s
	234.73	Engine Instruments	10s	234.73	Advance Throttles	10s
				234.89	Retard Throttles	3s
	235.00	Electronics Panel	2s	235.00	Switch to Ground Control	2s
	235.17	Thrust Control	2s	235.17	Thrust Control - Forward Idle	2s
Taxi	238.20	Cockpit	1m	238.20	Shut Down Check List	1m

TABLE D-X
CTOL (GA3) PILOT AND COPILOT WORKLOAD

TABLE X
CTOL (GA3) PILOT AND COPILOT WORKLOAD

Phase	Pilot Visual Task: Start Time	Task	Duration	Pilot Manual Task: Start Time	Task	Duration
Take-Off and Departure				-0.66	Hold Brakes	10s
	-0.63	Engine Instruments	10s	-0.63	Advance Throttles	2s
	-0.50	Scan Runway	33s	-0.50	Release Brakes	1s
				-0.50	Control Column, Rudder, Throttles	2.0m
				-0.33	Acknowledge V_1	1s
	0.00	Flight Instruments	1.5m	0.00	Acknowledge V_R, Rotate	3s
				0.08	Call for Gear Up (Right Hand Thumb Up)	1s
				0.18	Call for Flaps - 10°	1s
	0.26	Engine Instruments	3s	0.26	Reduce Power to Climb Setting	3s
				0.31	Call for Flap Retraction	1s
	1.5	Autopilot	3s	1.5	Engage Auto Pilot	3s
	1.55	Pitch Thumb Wheel & Flight Inst.	10s	1.55	Adjust Pitch Thumb Wheel for Desired ROC	10s
	1.72	Scan Flight Inst. & Engine Instruments (5 sec) every 20 sec.	180s			
	1.72	Flight Inst., Engine Inst., Cockpit	30s	1.72	Climb Check	30s
	8.00	Altimeter	5s	8.00	Set Altimeter 29.92	5s
				13.40	Acknowledge 1000 Feet to Cruising Altitude	1s
	13.42	Pitch Thumbwheel		13.42	Adjust Pitch Thumbwheel for Zero ROC	10s
Cruise	13.80	Scan Flight Instruments & Engine Inst. (5 sec) every 20s	24.22m			
	13.80	Monitor Mach. Meter, Engine Inst.	15s	13.80	Throttle	15s
	14.05	Flight Inst., Engine Inst., Cockpit	15s	14.05	Cruise Check	30s
	58.8	Monitor Mach. Meter, Engine Inst.	10s	58.8	Throttle	10s
Descent & Landing	105.7	Scan Flight Inst. & Engine Inst. (5 sec) every 20 sec.	165s	105.7	Advise Crew of Descent	2s
	105.73	Engine Instruments	3s	105.73	Throttle	3s
	106.23	Pitch Thumbwheel	10s	106.23	Adjust Pitch Thumbwheel for Desired ROD	10s
	106.4	Flight Inst., Mach. Meter, IAS	10s	106.4	Adjust Throttle	10s
	108 4	Flight Inst., Mach. Meter, IAS	10s	108.4	Adjust Throttle	10s
	108.57	Altimeter	5s	108.57	Set & Cross-ch :k Altimeters	5s
	110.4	Flight Inst., Mach. Meter, IAS	10s	110.4	Adjust Throttle	10s
	111.7	Flight Inst., Engine Inst., Cockpit	1m	111.7	Call for In-Range Check	1s
				111.7	In-Range Check	1m
	112.73	Monitor Airspeed	2s	112.76	Call for Flaps 15°	1s

TABLE D-X (cont'd)
CTOL (GA3) PILOT AND COPILOT WORKLOAD

TABLE X (cont'd)
CTOL (GA3) PILOT AND COPILOT WORKLOAD

Phase	Pilot Visual Task Start Time	Pilot Visual Task Task	Pilot Visual Task Duration	Pilot Manual Task Start Time	Pilot Manual Task Task	Pilot Manual Task Duration
Descent & Landing (Cont'd)	112.79	RMI	5s	112.79	Move Hdg Bug to Required Heading	5s
	112.87	Auto Pilot	3s	112.87	Auto Pilot - Hdg. Sel.	3s
	112.92	Monitor Airspeed	2s	112.95	Call for Flaps 25°	1s
	115.0	Auto Pilot	3s	115.0	Auto Pilot - Turn	3s
	115.05	Turn Knob	2s	115.05	Turn Knob	45s
	115.5	Monitor Airspeed	2s			
				115.53	Call for Gear Down	1s
	116.0	Auto Pilot	3s	116.0	Auto Pilot - ILS	3s
	116.47	Monitor Airspeed	2s			
				116.5	Call for Flaps 35°	1s
	116.63	Flight Inst., Engine Inst., Cockpit	20s	116.63	Landing Check	20s
	117.47	Monitor Airspeed	2s	117.5	Hand on Throttle	2.95m
	117.5	Monitor Flight Inst.	2.25m	117.5	Call for Full Flaps	1s
				118.0	Repeat Threshold & Final Approach Speed	2s
	119.75	Approach Lights & Runway	45s	119.75	Auto Pilot - Disengage	1s
				119.75	Control Wheel, Rudder	
				119.75	Throttle Back	2s
				120.0	Touchdown	
				120.0	Call - Buckets	1s
				120.20	Brakes	18s
Taxi	120.50	Taxi Way		120.50	Rudders & Brakes; Throttle	3m
	123.5	Cockpit		123.5	Shut Down Check List	1m

Phase	Copilot Visual Task Start Time	Copilot Visual Task Task	Copilot Visual Task Duration	Copilot Manual Task Start Time	Copilot Manual Task Task	Copilot Manual Task Duration
Departure	-0.50	Monitor IAS, Engine Inst., Flight Inst.	33s			
				-0.35	Notify Pilot V_1	1s
				-0.02	Notify Pilot V_R	1s
	0.07	Electronics Panel	2s	0.07	Switch from Tower to Dep. Cont.	2s
	0.10	Gear Handle	3s	0.10	Gear Up Handle	3s
	0.20	Gear Position Indicator & Flap Handle	3s	0.20	Flap Handle 10°	3s
	0.33	Flap Handle	3s	0.33	Flap Handle 0°	3s
	0.38	Electronics Panel	2s	0.38	Switch from ILS Freq. to VOR Freq.	2s
	0.41	Electrical Switch	2s	0.41	Seat Belt-Smoking Switch	2s
	0.44	Electronics Panel	8.6s	0.44	Select Nav. Freq.	8.6s
	0.59	Electronics Panel	8.6s	0.59	Select Comm. Freq.	8.6s
	0.73	Scan Flight Inst. & Engine Inst. (5 sec) every 20 sec.	197s			
	1.72	Flight Inst., Engine Inst. Cockpit	30s	1.72	Climb Check	30s
	8.00	Altimeter	5s	8.00	Set Altimeter 29.92	5s
	9.00	Electronics Panel	2s	9.00	Switch to Next Comm Freq.	2s
	9.03	Electronics Panel	8.6s	9.03	Select Comm. Freq.	8.6s
				13.38	Notify Pilot 1000 Feet to Cruising Altitude	1s

TABLE D-X (cont'd)
CTOL (GA3) PILOT AND COPILOT WORKLOAD

TABLE X (cont'd)
CTOL (GA3) PILOT AND COPILOT WORKLOAD

Phase	Copilot Visual Task			Copilot Manual Task		
	Start Time	Task	Duration	Start Time	Task	Duration
Departure (Cont'd)	13.80	Scan Flight Inst. & Engine Inst. (5 sec) every 20 sec.	24.22m			
	14.05	Flight Inst., Engine Inst., Cockpit	30s	14.05	Cruise Check	30s
	14.55	Electronics Panel	2s	14.55	Switch to Next Nav. Freq.	2s
	14.58	Electronics Panel	8.6s	14.58	Select Next Nav. Freq.	8.6s
	29.0	Electronics Panel	2s	29.0	Switch to Next Comm. Freq.	2s
	29.03	Electronics Panel	8.6s	29.03	Select Comm. Freq.	8.6s
	59.00	Electronics Panel	2s	59.00	Switch to Next Nav.Freq.	2s
	59.03	Electronics Panel	8.6s	59.03	Select Next Nav. Freq.	8.6s
	60 00	Fuel Gages, Writing Board	10s	60.00	Fill Out Fuel Sheet	10s
	80.00	Electronics Panel	2s	80.00	Switch to Next Comm.Freq	2s
	80.03	Electronics Panel	8.6s	80.03	Select Next Comm. Freq.	8.6s
	80.17	Electronics Panel	2s	80.17	Switch to Next Nav.Freq.	2s
	80.20	Electronics Panel	8.6s	80.20	Select Next Nav. Freq.	8.6s
	100.00	Electronics Panel	2s	100.00	Switch to Next Comm.Freq	2s
	100.03	Electronics Panel	8.6s	100.03	Select Approach Control Freq	8.6s
	100.17	Electronics Panel	2s	100.17	Switch to Next Nav.Freq.	2s
	100.20	Electronics Panel	8.6s	100.20	Select ILS Freq.	8.6s
Descent	105.7	Scan Flight Inst., Engine Inst. (5 sec) every 20 sec	165s			
	108.57	Altimeter	5s	108.57	Set & Cross-check Altimeter	5s
	111.7	Flight Inst., Engine Inst., Cockpit	1m	111.7	In-Range Check	1m
	112.78	Flap Handle	3s	112.78	Flap Handle 15°	3s
	112.95	Flap Handle	3s	112.95	Flap Handle 25°	3s
	114.97	Electronics Panel	2s	114.97	Switch to ILS Freq.	2s
	115.55	Gear Handle	3s	115.55	Gear Down	3s
	116.5	Flap Handle	3s	116.5	Flap Handle 35°	3s
	116.63	Flight Inst., Engine Inst., Cockpit, Writing Board	20s	116.63	Landing Check	20s
	117.5	Flap Handle	3s	117.5	Flap Handle Full	3s
	117.55	Electronics Panel	2s	117.55	Switch to Tower Freq.	2s
	117.58	Electronics Panel	8.6s	117.58	Select Ground Control Freq.	8.6s
				118.0	Call Out Threshold & Final Approach Speed	2s
	118.5	Monitor Engine Inst. & Watch for Runway	1.25m	118.05	Seat Belt & Smoking Switch	2s
				119.95	Throttle	45s
	120.0	Thrust Control	2s	120.0	Thrust Control - Reverse Idle	2s
	120.03	Engine Inst.	10s	120.03	Advance Throttles	10s
			3s	120.19	Retard Throttles	3s
	120.30	Electronics Panel	2s	120.30	Switch to Ground Control	2s
	120.47	Thrust Control	2s	120.47	Thrust Control - Forward Idle	2s
Taxi	123.5	Cockpit	1m	123.5	Shut Down Check List	1m

TABLE D-XI
GA2 PILOT WORKLOAD

Phase	Pilot Visual Task: Start Time	Task	Duration	Pilot Manual Task: Start Time	Task	Duration
Taxi	-6.56m			-6.84m	Adjust Seat, Fasten Seat Belt, Lock Doors	17s
	-6.56	Brake Handle	5s	-6.56	Set Brakes	5s
	-6.48	Check Radios and Electrical Switches – OFF	5s			
	-6.39	Ignition Switch	2s	-6 39	Ignition Switch – ON	2s
				-6 36	Crack Throttle	3s
	-6.31	Master Switch	2s	-6 31	Master Switch – ON	2s
	-6.28	Clear Area	7s			
				-6.16	Contact	7s
	-6.04	Monitor RPM, Oil Pressure	20s	-6.04	Adjust Throttle	2s
	-5.71	Check for other Aircraft	5s			
	-5.62	Brake Handle	2s	-5.62	Release Brakes	2s
	-5.59	Check for other Aircraft	3.03m	-5.59	Open Throttle	2s
				-5.56	Control Wheel, Rudder, Brakes	3m
	-2.56	Brake Handle	5s	-2.56	Set Brakes	5s
	-2.48	Monitor RPM	2s	-2.48	Open Throttle	2s
	-2.44	Monitor Oil Press	2s			
	-2.41	Monitor Ammeter	2s			
	-2.38	Monitor Oil Temp.	2s			
	-2.34	Monitor Cylinder Head Temp.	7s			
	-2 31	Monitor RPM	6s	-2 31	Check Prop. Pitch Control	2s
				-2 28	Check Left Mag	2s
				-2 24	Check Right Mag	2s
				-2 21	Close Throttle	
	-2 17	Scan Aircraft Control Surfaces	9s	-2 17	Check Free and Correct Movement of Controls	9s
	-2.03m	Scan Flaps and Flap Position Indicator	5s	-2.03m	Check and Set Flaps	5s
	-1 94	Monitor Clock	3s	-1 94	Set Clock	3s
	-1 89	Monitor Altimeter	3s	-1 89	Set Altimeter	3s
	-1 84	Monitor DG	3s	-1 84	Set DG	3s
	-1 79	Scan Rudder and Elevator Trim Position Indicators	5s	-1 79	Set Rudder and Elevator Trim	5s
	-1 71	Scan Fuel Selector Valve Position		-1 71	Check Fuel on Proper Tank	3s
	-1 66	Monitor Frequency Selection	8.6s	-1 66	Set Radio	8.6s
	-1 52	Brake Handle	2s	-1 52	Release Brakes	2s
	-1 48	Check For Other Aircraft	1.05m	-1 48	Open Throttle	2s
				-1 4[illegible]	Control Wheel, Rudder, Brakes	1 95s
T/O and Departure	-0 45	Monitor Engine Instruments, Airspeed, TK, Attitude, Altitude (5 sec.) every 30 sec.	95s	- 45	Open Throttle	2s
				- 45	Control Wheel Rudder	9m27
				0	Rotate	
				0 05	Retract Gear and Flaps	4s
	0 15	Check Gear and Flaps-Up	3s			
	0 20	Monitor MP	3s	0 20	Adjust Throttles	3s
	0 25	Monitor RPM	3s	0 25	Adjust Propellers	3s
	0 30	Monitor Frequency Selection	8.6s	0 30	Set Radio	8.6s

Phase	Pilot Visual Task: Start Time	Task	Duration	Pilot Manual Task: Start Time	Task	Duration
	0 44m	Monitor Airspeed	10s	0 44m	Adjust Trim	10s
	0 61	Heat and Vent Control	5s	0 61	Adjust Heating and Vent	5s
	8.86	Monitor Frequency Selection		8 86	Select Frequency	8.6s
		Check for other Aircraft During Remainder of Time			Check for other Aircraft During Remainder of Time	
Cruise	9 0	Monitor Engine Instruments, Airspeed, TK, Attitude, Altitude (5 sec.) every 30 sec.	25.12m	9 0	Control Wheel, Rudder	150 7m
	9 0	Monitor MP	3s	9 0	Adjust Throttle	3s
	9 05	Monitor RPM	3s	9 05	Adjust Prop.	3s
	9 10	Monitor EGT	3s	9 10	Adjust Mixture	3s
	9 15	Monitor Mag Heading and DG (10s) every 15 min.	100s	9 15	Update DG every 15 min.	10s
	142 1	Monitor Frequency Selection	8 6s	142 1	Select Frequency	8 6s
Descent	159 7	Monitor Engine Instruments, Airspeed, Attitude, Altitude, TK (5 sec) every 30 sec.–	190s	159 7	Control Wheel, Rudder	20 25m
	159 73	Check Fuel on Proper Tank	3s	159 7	Adjust Mixture – Rich	2s
	159 78	Monitor MP	3s	159 78	Set Throttle	3s
	159 82	Monitor Airspeed	10s	159 82	Adjust Trim	10s
	175.55	Monitor Frequency Selection	8.6s	175.55	Select Frequency	8.6s
Approach and Landing	175.70m	Monitor Engine Instruments, Airspeed, Attitude, Altitude, TK (5 sec) every 30 sec.	45s	175.70m	Control Wheel, Rudder	4.40m
	175.70	Monitor MP		175.70	Adjust Throttle	3s
				175 75	Adjust Prop – High RPM	2s
	175.78	Monitor Airspeed	2s			
				175.81	Gear Down	2s
	175.91	Check Gear Down	2s			
	175.95	Monitor Airspeed	2s			
				175.98	Flaps Down	3s
	176.03	Monitor Airspeed	10s	176 03	Adjust Trim	10s
	176.20	Monitor Airspeed	3s	176 20	Adjust Throttle	3s
				180 00	Close Throttle	2s
				180 10	Retract Flaps	2s
		Check for Other Aircraft During Remainder of Time				
Taxi				180 45	Control Wheel, Rudder, Brakes	3[illegible]
	180 45	Monitor Frequency Selection	8.6s	180 45	Select Frequency	8 6s
	183.45	Brake Handle	5s	183 45	Set Brakes	5s
	183.53	Radio and Electrical Switches	5s	183 53	Radio and Electrical Switches – OFF	5s
	183.62	MIXTURE Control		183 62	Adjust Mixture – LEAN	2s
	183.73	Mag Switch	2s	183 73	Mags – OFF	2s
	183.77	Master Switch		183 77	Master – OFF	2s

APPENDIX E

NAVTRACS GROUND AND AIRBORNE SYSTEM COSTS

Costs of ground and airborne equipments - e.g., Omega, VORTAC, Decca, Loran C, and NAV SAT ground stations - including both developmental and maintenance costs, were compiled and tabulated in Appendix E. Avionics equipment costs for air carrier and general aviation installations are also tabulated. Costs were compiled from a series of references including Ref. [52] and Ref. [93].

E.1. AREA NAVIGATION SYSTEM COSTS

Table E-I lists area navigation system costs, including unit cost and annual maintenance. Airborne avionics costs for air carrier and general aviation are separately tabulated.

TABLE E-I (**)
AREA NAVIGATION SYSTEM COST

SYSTEM	GROUND STATION			AIR CARRIER AND GA3		GA1, GA2.	
	Unit Cost $\times 10^3$	No. of Units	Annual Maint. $\times 10^3$	Unit Cost $\times 10^3$	Annual Maint. $\times 10^2$	Unit Cost $\times 10^3$	Annual Maint $\times 10^2$
LORAN A	700 [1] 560 [2]	80 [3]	85.4 [4] 92.3 [5]	4.0 to 9.5	8.0	1.5 to 4.0	1.0
LORAN C	3,145 [6] 4,152 [7] 7,105 [8]	25 217.9 [5]	198.8 [4]	15 K [10]	-	5 [11]	--
OMEGA	9,000	3	0.3 *	-	-	-	-
VORTAC	213	≈850	29.3 [9]	15	2.5	3.9	2.0
CONSOL	900	9	95	-	-	-	-
INERTIAL	-	-	-	85 to 125	-	-	-
DOPPLER	-	-	-	50	-	-	-
NAV SAT (Ref. 93)	** [12]	-	-	15	-	15	-
NAV SAT (Ref. 52)	-	-	-	70 to 33	-	19 to 6 [13]	-
ILS	235	-	-	** [14]	** [14]	** [14]	** [14]
AILS	-	-	-	-	-	-	-
DECCA	1,500	-	-	-	-	-	-
PAR	-	-	≈100 [15]	-	-	-	-

* Estimate
** (See footnotes on following page.)

1 Foreign based

2 Contiguous U. S.

3 43 U. S. Funded

4 Atlantic Ocean Area

5 Pacific Ocean Area

6 Temperate Zone

7 Tropic Zone

8 Arctic Zone

9 Doesn't include annual charges for control circuits, site leasing, etc.

10 Has cycle matching feature

11 No cycle matching

12 Cost broken down as follows:

R and D	$ 66,000,000
Spacecraft	14,000,000
Ground Station	15,000,000
Ground Station Operations	10,000,000/year
	$106,000,000

13 Lower figure is based on ground based computations

14 ILS capability is usually contained in the equipment used with the VORTAC system

15 Includes Operators

APPENDIX F

CANDIDATE NAVIGATION SYSTEMS

F.1 INTRODUCTION

This Appendix presents the results of a review and analysis of nine candidate navigation aids which was undertaken to determine their suitability for use as primary aids in the navigation ATC system. The contractor was obligated to examine the four systems listed as items 2, 3, 7 and 8, below. In addition, growth versions of three of the systems were postulated and evaluated. They are listed as items 4, 5 and 6. Omega and VOR/DME, systems 1 and 9 respectively, were also evaluated for completeness.

Ground Based Time Difference Aids (GBTD)

1 VLF/CW (Omega)
*2 LF/CW (Decca)
*3 LF/Pulse (Loran C)

Differential Time Difference Systems (DTD)

4 VLF/CW
5 LF/CW
6 LF/Pulse

Other Systems

*7 Navigation Satellite
*8 Radio-Inertial
9 VOR/DME

*Indicates the systems for which an evaluation was required

Operational advantages, disadvantages and principal differences of each of the systems are discussed and a detailed accuracy analysis is presented.

F.2 GROUND BASED TIME DIFFERENCE SYSTEMS

Time difference position fixing (PF) systems have several attributes that make them worthy of consideration for an advanced navigation-air traffic control system. The following paragraphs contain some of the principles of operation upon which time difference systems are based. The attributes and deficiencies of these systems are presented to demonstrate the physical advantages and limitations of time difference navigation aids. No comparison as to the relative merits of existing time difference systems or concepts is to be implied; however, examples of existing systems are used where appropriate.

F.2.1 System Constraints

This study is structured around the pilot's requirements for a future navigation/air traffic control system. Some physical parameters of a ground based time difference system can be ascertained from three of the navigation operational requirements. These three requirements are:

(1) Line of sight independent
(2) Minimal number of ground stations
(3) Satisfy accuracy constraint

The combination of the first two requirements implies that beyond-the-horizon coverage is desirable. This constrains the operating frequency of the system to frequencies in the VLF and LF spectrum. The choice of operating frequency within this spectrum is basically a trade-off between accuracy and coverage area. The fundamental merits and deficiencies of ground based time difference systems are discussed in the remainder of this section.

F.2.2 Principle of Operation

This section contains a description of the geometry of TD systems and a discussion of the radio signals.

F.2.2.1 TD Geometry

A user's line of position (LOP) is formed by measuring the difference in the time of arrival of synchronized signals emanating from two remote transmitters. The line of constant time difference is a hyperbola with the two transmitters as foci. Hence these systems are often called hyperbolic navigation aids. The intersection of two hyperbolic LOP's yields the user's position. In most applications three transmitters are used. One transmitter designated the master station is used in both of the time difference measurements. The other two stations are called slaves. The master and slave stations are collectively called a chain. The lines between the master and slave stations are called baselines and the extension of this line beyond the stations is called the baseline extension. The geometric properties (called GDOP for geometric dilution of precision) of time difference systems are such that the highest position-fixing accuracy is available in the area between the baselines and little or no coverage is obtained on or near the baseline extensions. Figure F-1 indicates a typical hyperbolic system geometry. The angle between the baselines is usually between 120° - 150°. This range of angles represents a compromise between coverage and accuracy. The coverage area can be increased significantly when a third slave station is added as shown in Figure F-2. A signal flow diagram for a ground based TD system is shown in Figure F-3. The monitor station provides the time synchronization for the chain. The monitor station receives the signals

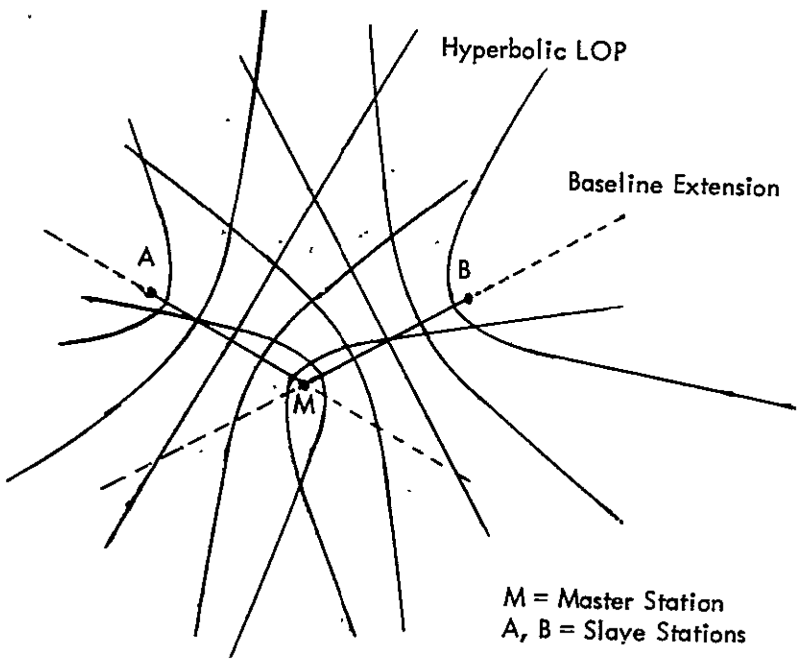


Figure F-1. Typical Hyperbolic System Geometry

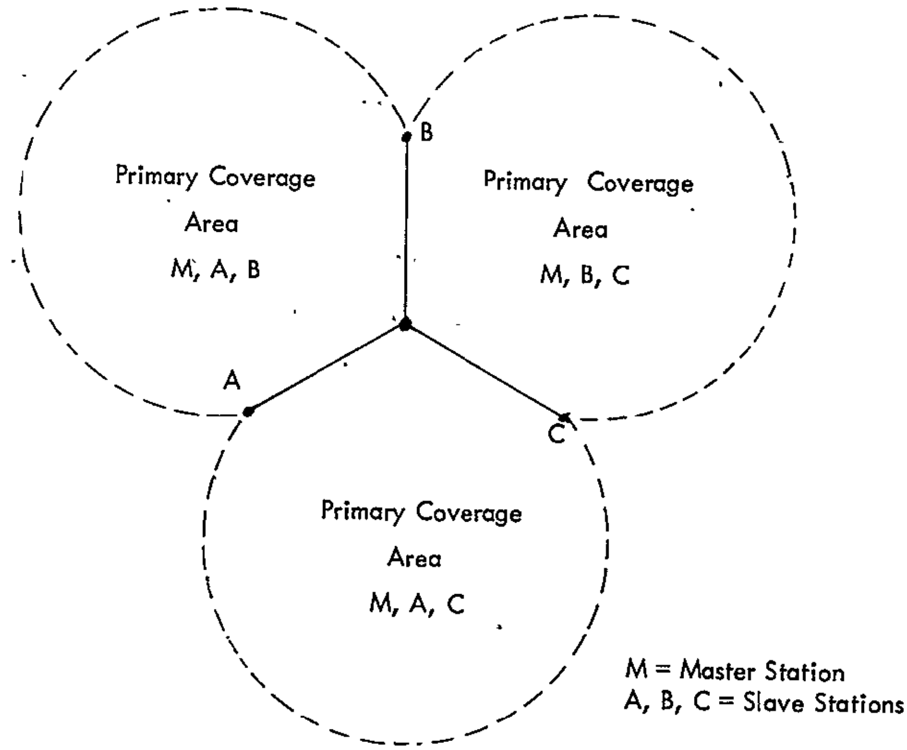


Figure F-2. Three Slave Configuration

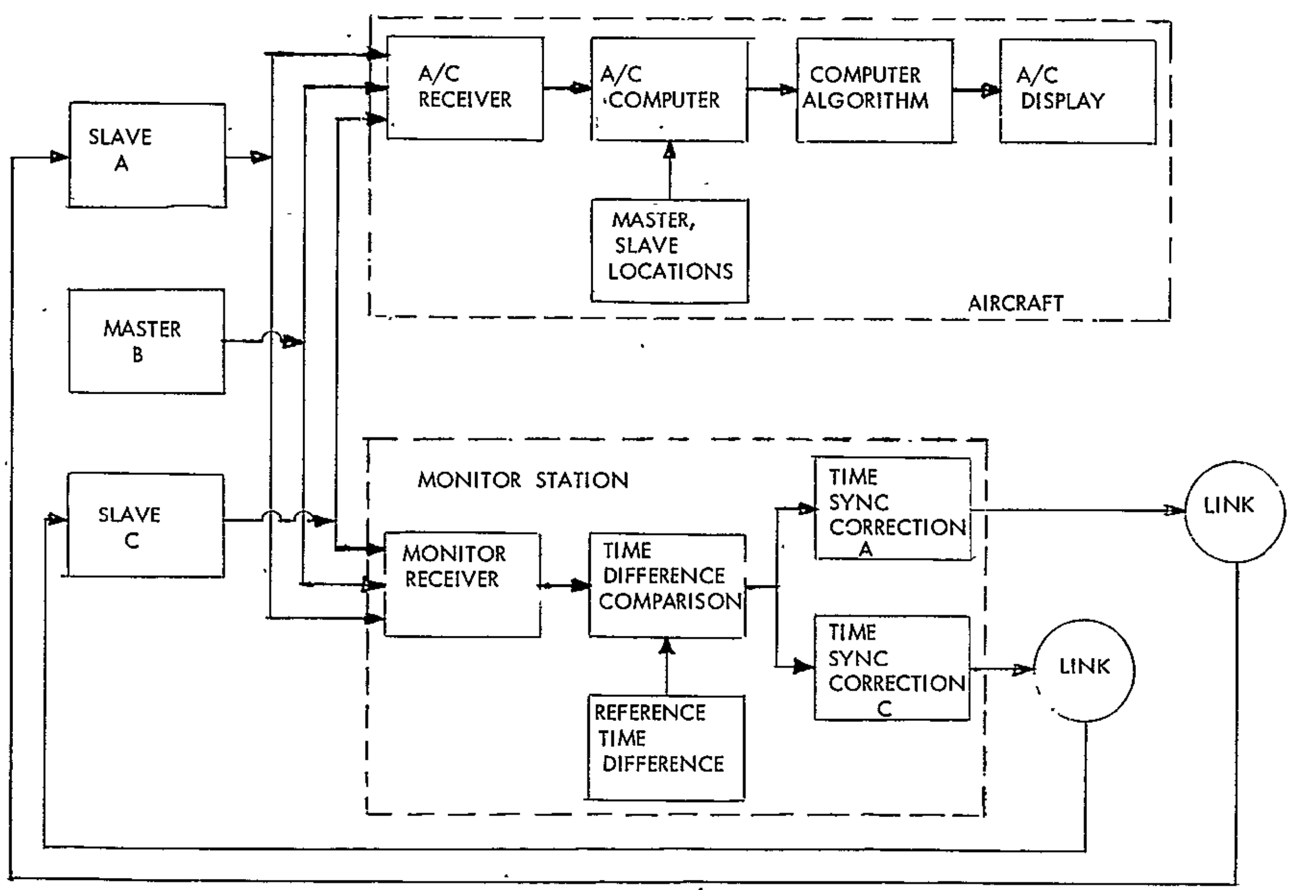


Figure F-3. Ground Based Time Difference System in the same manner as a user aircraft. However, the monitor receiver is in a stationary environment; thus the time difference signals are nominally constant. Variations in the received signal are caused by the reception of atmospheric noise and drifts in the local oscillators of the master and slave stations. The atmospheric noise has a much higher frequency content than the oscillator drift. The oscillator drift can thus be identified by filtering the received time difference signals and comparing the output to a standard time difference reference. Synchronization data is then data-linked back to the slave stations for correction.

F.2.2.2 Radio Frequency Signals

The radio frequency signals are the medium through which the user aircraft obtains its position data. Therefore it is important to know how environmental and physical factors affect these signals. Among the important factors that are discussed in this section are:

(1) propagation media (groundwave, skywave)
(2) signal modulation (pulsed, CW)
(3) atmospheric noise
(4) diurnal variations
(5) surface irregularities (conductivity, mountains)
(6) aircraft dynamics

F.2.2.2.1 CW Signals

Both pulsed and CW signals may be used in TD systems. Phase comparison of the TD signals is a relatively straightforward signal processing function. However, the phase repeats at a distance of $\lambda/2$ along the baseline, where λ is the wavelength of the signal. This repetition of the phase produces ambiguities in the time difference readings which must be resolved. A widely used technique for resolving these ambiguities is multiple frequency transmissions. A frequency of $f + \Delta f$ is transmitted during part of the transmission period where f is the nominal operating frequency and Δf is a fractional frequency deviation on the order of .1f to .2f. Phase comparisons can be made at the frequency Δf and the ambiguity can be resolved to the wavelength corresponding to Δf.

F.2.2.2.2 Pulsed Signals

Pulsed signals have some operational advantages over the CW signals. Ambiguity resolution is unnecessary if the pulses are separated sufficiently in time (approximately 1 ms for each one hundred kilometers of baseline length). In addition, pulsed signals can be used to discriminate against skywave contamination in those systems that rely upon groundwave propagation. However, the pulse measurement quite definitely has limitations. Leading edge comparison is not sufficiently accurate for navigation purposes due to the limited available bandwidth in the VLF and LF signals. In order to retain pulse advantages but also yield accurate navigation data, phase measurements are made on the carrier frequency and the pulse envelope is used to resolve the ambiguity. The pulse systems incur a penalty with respect to the CW systems in the rejection of atmospheric noise. The signal is available for only a fraction of the transmitting period. Consequently, the average power at the receiver input is far below the peak received power. To offset this reduction in average power, high peak power and long averaging times are required. The long averaging times can create instability in high performance aircraft receivers. Often the receiver must be supplied with external velocity inputs.

F.2.3 Accuracy of Ground Based TD Systems

The accuracy of a ground based TD system is a function of many parameters. Several of these parameters are discussed and first estimates of the magnitude and variations of several error sources are presented.

F.2.3.1 General Discussion of Errors

In order to discuss accuracy and errors, it is first necessary to define what is meant by these words. In order to define an error, it is necessary to observe a measurement and compare this measurement with some reference standard. The choice of the reference is obviously very important. The position reference that is used in this report for enroute flight legs is geocentric latitude and longitude as obtained from an accurate survey. An information flow diagram of the TD receiver and coordinate converter with error inputs is shown in Figure F-4.

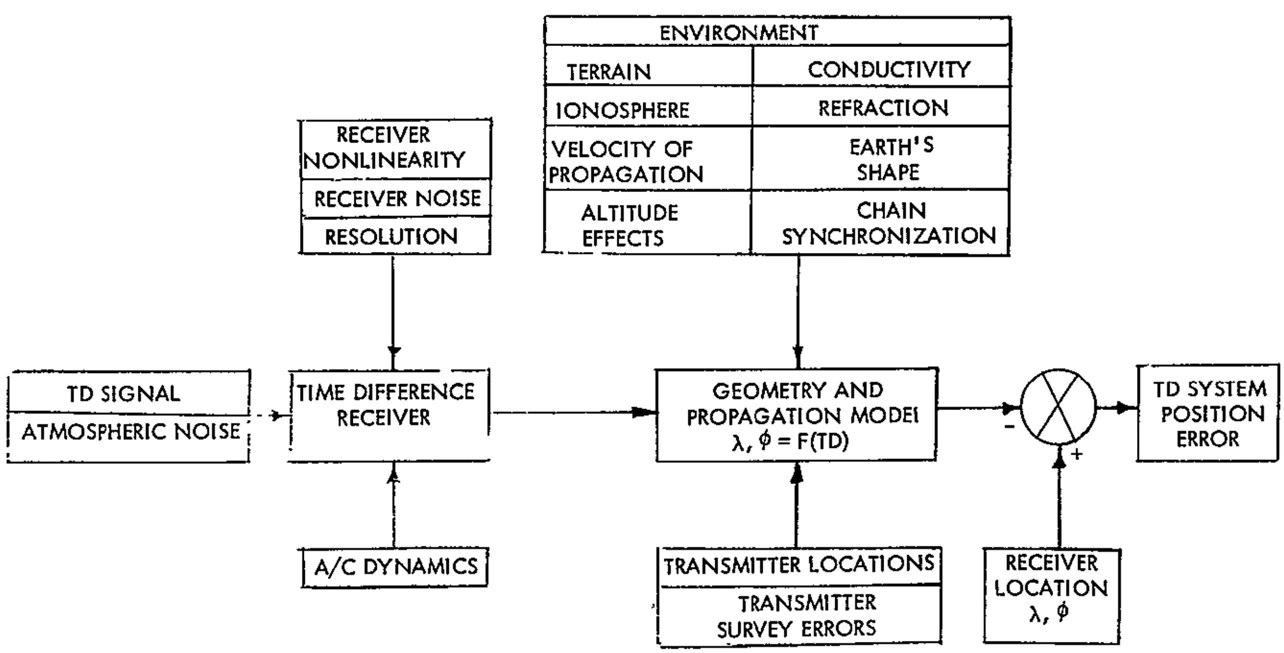


Figure F-4. Information Flow Diagram for TD System Errors

The geometry and propagation model indicated in the center of the diagram may be a stored computer program in an onboard or ground computer, or it may be a chart that was prepared from a geometry and propagation model. The error in position as found from the receiver/coordinate converter is a function of the ability of the receiver to:

(1) provide sufficient resolution
(2) discriminate against atmospheric noise
(3) contribute minimal internal set noise
(4) accurately track aircraft maneuvers ....

and of the coordinate converter to utilize an accurate model of the geometry and propagation variables in order to minimize errors due to:

(1) velocity of propagation as a function of distance
(2) aircraft altitude
(3) atmospheric refraction
(4) terrain anomalisms such as mountains
(5) conductivity variation in the earth's surface
(6) oblate earth
(7) ionospheric variations.

Two additional error sources may occur due to improper chain installation and operation. These are:

(1) errors in the synchronization of the transmissions from the master or slave stations

(2) survey errors in the location of the transmitters.

F.2.3.2 Error Classification

Errors in navigation systems are described in several ways. Some authors prefer the terms random and systematic errors; others prefer to use bias rather than systematic errors; in addition, the terms predictability and repeatability, and relative error, are often used. In this report the latter terms will be used in the following way:

(1) repeatability errors: those errors which affect a user's ability to repeat a flight path at a different time and measure the same time differences.

(2) predictability errors: those errors which affect a user's ability to predict values of time differences at a given point. These errors are essentially constant with time at a given point.

(3) relative errors: those errors which affect the ability of two users at different points to obtain their relative position from the TD measurements. An important consideration for relative error is the gradient of predictability error with distance.

The error sources for three TD concepts are discussed in the following paragraphs.

F.2.3.3 CW System/VLF Receiver

VLF systems make use of stable skywave signals. The earth and ionosphere form a spherical waveguide in which the VLF signals propagate for very long distances. Several modes are present in this waveguide just as in typical microwave waveguides. However, at long distances one mode is dominant. For instance, at ranges greater than 600 nmi for a 10 KHz signal, one mode is dominant and navigation information can be obtained from phase measurements upon this signal.

F.2.3.3.1 Dynamic Error and Atmospheric Noise Error Trade-Off

The navigation receiver is assumed to have a phase locked tracking loop for each transmitter. The transfer function for this loop is assumed to have Type 2 feedback control system characteristics. An analysis of such a tracking loop is contained in Section F.2.5. The receiver constant B is established as a trade-off between dynamic response errors and atmospheric noise errors. From Equation (62), Appendix F, Section F.2.4.1, the dynamic response error is:

$$\delta t = \frac{a}{cB^2} \quad \mu s \tag{1}$$

where a = aircraft acceleration (m/sec^2)

c = velocity of propagation (300 m/μs)

B = receiver constant (rad/sec)

and from equation (27), the rms noise error is:

$$\sigma_t = \frac{.0502\sqrt{B}}{f} \left(\frac{n}{s}\right) \quad \mu s \tag{2}$$

where f = carrier frequency

B = receiver constant

n = rms noise field strength density ($\mu V/m/Hz^{\frac{1}{2}}$)

S = rms signal field strength (μV/m).

Pessimistic noise and acceleration figures are used in the following analysis to yield a result for the receiver bandwidth. The three-sigma acceleration is assumed to be a 2g lateral acceleration upon the aircraft. The transmitter is assumed to produce a 10kHz signal with 10kW of radiated power. The 10kW figure is the operational goal of the Omega system and thus represents a realistic SOA power output The atmospheric noise is taken from CCIR Report No. 322 [79]. The noisiest four-hour period during the year in the New York City area is the time from 0000 to 0400 hours during a summer night. A log normal distribution curve was computed as per instructions in the report and the hourly average noise value, exceeded only 1% of the time, was estimated and used in the computations. This value was:

$$n = 53 \ \mu v/m/(Hz)^{\frac{1}{2}} \tag{3}$$

The field strength was computed from a formula from Watt and Plush [81].

$$E \approx K + Pr - 10 \log_{10}(f_{kHz}) - 10 \log_{10}[a \sin d/a] - \alpha d/1000 \tag{4}$$

where $E \doteq$ vertical field strength (db above 1 μv/m)

Pr = radiated power (db above 1 kW)

f_{kHz} = carrier frequency (kHz)

a = radius of the earth ($\approx$ 6,400 km)

d = distance from the transmitter (km)

K = constant (94.8 db - night, 97.5 db - daytime)

α = attenuation constant.

Watt and Plush use an extrapolated value of $\alpha \doteq 4.5$ db/1000 km; however, later theoretical and experimental estimates are α = 3 db/1000 km. Using the later value for α and a distance of 6000 nmi,

$$S \approx 10^{E/20} = 14.8 \ \mu v/m \tag{5}$$

The dynamic error and the rms noise error were equated to estimate a trade-off receiver constant. As a result

$$B = .106 \text{ rad/sec}$$

and $\delta t \approx 6.0 \ \mu s$

A time error of 6.0 μs corresponds to a phase error of 22° at 10 kc. This is certainly marginal performance for the VLF receiver. Much better performance could be obtained by reducing the receiver constant B to improve the noise performance and by providing rate aiding for the tracking loop to improve the dynamic response of the receiver and thus reducing the steady state acceleration error. This requires some onboard computation facility to resolve radial and tangential velocity components.

In addition to the atmospheric noise and dynamic response errors, several other error sources influence the TD system.

F.2.3.3.2 Diurnal Variations

The reflecting height of the ionosphere varies with the time of day. This is due to the solar energy incident upon the free electrons in the ionosphere. This, in effect, changes the dimensions of the waveguide, which in turn changes the phase of the transmitted signal. Correction tables for this diurnal phase shift, based upon an ionospheric model, can be calculated. Such corrections have been calculated for the 10.2 kHz Omega signal. Swanson [82] has indicated that from 13,000 hours of measurements from widely separated locations the rms LOP variations range from 3 μs during the day (13.6 kHz) to 6 μs at night (10.2 kHz). The total change in phase is on the order of 50 μs. The correction of the diurnal shift is a function of time of day and user's position. Corrections would contribute to pilot workloading if manual look-up and addition tasks were required. No additional workload for navigation tasks are required for the user who has stored-corrections in an onboard computer or for the user who is connected to a ground computer via a data link.

F.2.3.3.3 Precipitation Static

The discharge of charged water vapor particles upon the receiving antenna has produced sufficient noise to cause loss of signal in early aircraft antennas. Development of properly shielded antennas has shown promise of reducing this problem.

F.2.3.3.4 Resolution and Instrument Error

Resolution of the phase-locked tracking loop is approximately 0.1 μs. Internal receiver noise also produces a very small error in the output time difference measurements.

F.2.3.3.5 Mode Interference

The spherical waveguide produces at least two prevalent modes. In some regions close to the transmitters, both modes are present and can cause erroneous phase measurements.

F.2.3.3.6 Phase Anomalies

Sudden ionospheric disturbances have been observed to introduce time shifts of up to 50 μs. The peak of the disturbance may occur as soon as 15 minutes after the beginning of the disturbance and the entire disturbance has been observed as long as 1.5 hours.

Magnetic storms and meteor shower ionization have been observed as causing phase anomalies. Pierce [83] observed phase jitters(at night) of 5 μs during magnetic storms; and Chilton [84] observed deviations of 14 μs from the monthly average for meteor shower ionization.

Errors of the magnitude of those caused by SID's, and to a lesser extent the magnetic storms and meteor shower ionization,would cause large errors of up to 10 miles in the PF capability of the system. These errors are not within the accuracy constraints for the 1975-85 navigation accuracy requirement. Thus corrections for phase variations due to phase anomalies must be incorporated into any VLF system for use as a primary navigation aid. Either reliable prediction procedures must be incorporated or ground station calibration procedures must be defined to reduce errors caused by phase anomalies.

F.2.3.3.7 Coordinate Transformation and Station Locations

Coordinate transformations must relate the time difference measurements to points on the earth through some algorithm and a model of the geoid. The standard model of the geoid for survey purposes is an ellipsoid of revolution about the polar axis, or it is also called an oblate spheroid. Land surveys have made use of different major and minor axes of the ellipse in various areas of the world. Mathematical expressions are available for computation of distance and azimuths on the surface of the ellipsoid. Simple spherical trigonometry can produce errors of 9 nmi at a distance of 6000 nmi, so correction terms are necessary if spherical trigonometry is used. An error of one hundred parts per million is assumed.

Transmitting station positions must be known to a high degree of accuracy if the user is to find his position accurately. With the geodetic survey satellites such as SECOR, the limitation in station location is the accuracy with which the control stations are known [Ref 85]. An accuracy of 10 parts per million has been assumed.

F.2.3.3.8 Summary of VLF Error Sources

A design point system with the following parameters was analyzed:

System	VLF time difference
Frequency	10 kHz
Transmitter power	10 kW
Design range	600-6000 nmi
Aircraft acceleration	2g.

Receiver Tracking Loop	Type II, critically damped, feedback control system, no rate aiding
Noise environment	0000-0400 hrs summer night, New York City; hourly average noise exceeded only 1% of the time.

The time difference accuracies are for independent paths:

$$\sigma_{TD1}^2 = \sigma_{P1}^2 + \sigma_{P2}^2 \tag{6}$$

$$\sigma_{TD2}^2 = \sigma_{P3}^2 + \sigma_{P2}^2 \tag{7}$$

where σ_{TDi} = standard deviation of i th time difference

σ_{Pj} = standard deviation of j th path error

Scott [84] has shown contours of constant error due to GDOP. Most areas lie inside a contour of K = 1.0 where

$K = d\ rms/c\Delta t$

where d rms = rms radial error

c = velocity of propagation

$\sigma_{\Delta t}$ = time difference error ($\sigma_{TD1} = \sigma_{TD2} = \sigma_{\Delta T}$)

Expected performance of the VLF time difference system would be estimated as shown in Table F-I.

F.2.3.4 LF System/CW Receiver

Low frequency PF systems make use of the phase of a very

TABLE F-1
VLF/CW SYSTEM ERRORS

	Time (μs)	Time Diff (μs)	Location 1* (nmi)	Location 2** (nmi)
REPEATABILITY ERRORS				
Resolution and Receiver Noise	0.5	0.71	0.115	0.115
Atmospheric Noise - Location 1	2	2.83	0.458	
Atmospheric Noise - Location 2	6	8.49		1.375
Acceleration Error	· 1.5	2.12	0.343	0.343
PREDICTABILITY ERRORS				
Diurnal Phase Shift				
Uncorrected	50	70.71	11.45	11.45
Night Corrected	18	25.46	4.14	4.14
Day Corrected	9	12.73	2.07	2.07
Transition Corrected	12	16.97	2.76	2.76
Oblate Earth - Location 1	0.0001D	0.42	0.07	
Oblate Earth - Location 2	0.0001D	0.85		0.14
Station Location	0.5	0.71	0.12	0.12
Phase Anomalies (SID)	50	70.71	11.45	11.45
POSITION ERRORS: REPEATABILITY			.58	1.42
PREDICTABILITY - Day			2.15	2.52
Night			4.18	4.38
Transition			2.82	3.11
SID			12.19	12.26

D = Mean Distance to Transmitters
*Location 1 - D = 3000 nmi
**Location 2 - D = 6000 nmi

stable ground wave signal to obtain position information. The LF systems are capable of medium range applications. The range of a CW system for aircraft operation is 10-200 miles from the transmitter. The range is limited by altitude errors due to slant range effects at close range and skywave contamination at night at long range.

F.2.3.4.1 Atmospheric Noise and Dynamic Errors

The following system parameters are compatible with present off-the-shelf equipment and are chosen for error analysis:

System: LF-CW Time Difference

Frequency: 100 KC

Power: 600 W radiated power

Range: 200 miles over land (σ = .005 mho/meter)

Aircraft Acceleration Limit = 2g

Atmospheric Noise: 13.7 μv/m in 1Hz bandwidth (hourly average noise exceeded only 1% of the time in New York City area during the noisiest four-hour period of the year - 0000-0400 hours, summer night [Ref 79])

Signal Field Strength: 515 μv/m @200 miles [Ref 86]

Equating the time errors for a CW receiver for atmospheric noise and dynamic lag due to acceleration from Section F.2.5, the trade-off receiver constant is

$$B = 1.88 \text{ rad/sec}$$

and the corresponding design error is

$$\delta t \leq .0185 \ \mu s$$

This is a very acceptable upper bound on the error. Consequently, rate aiding appears unnecessary for a CW receiver that operates within the above constraints.

F.2.3.4.2 Ionospheric Effects

The primary limitation upon LF/CW ground wave systems is the interfering effects of the reflected signal from the ionosphere. This reflected wave has an arbitrary phase shift with respect to the ground wave and thus causes phase errors. This effect is shown in the phasor diagram of Figure F-5.

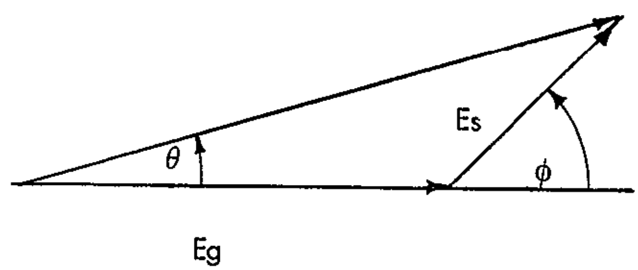


Figure F-5. Sky Wave, Ground Wave Phasor Diagram

The resultant phase error θ is

$$\theta = \tan^{-1}\left(\frac{Es \sin \phi}{Eg + Es \cos \phi}\right) \quad (8)$$

where Es = skywave field strength

Eg = ground wave field strength

ϕ = arbitrary phase angle

The maximum phase error is

$$\theta = \sin^{-1}\left(\frac{Es}{Eg}\right) \quad (9)$$

Williams [Ref 87] presents the formula

$$Es = \frac{2Eo}{D}\,\psi\,\frac{D^2}{D^2 + 4H^2} \quad (10)$$

For distances up to 200 miles the ground wave field strength is approximately

$$Eg \approx \frac{Eo}{D} \quad \text{so that for small angles} \tag{11}$$

$$\theta \approx \frac{2\psi D^2}{D^2 + 4H^2} \tag{12}$$

The resulting time error is plotted in Figure F-6. At night the reflection coefficient increases significantly from the day value. The increase in time error is sometimes referred to as the "night effect".

At distances greater than 200 nmi, the ground wave assumes a greater attenuation rate than that of Eo/D. Meanwhile the skywave is approaching an attenuation rate proportional to 1/D and at a distance of about 400 miles the nighttime skywave and the ground wave are equal in amplitude.

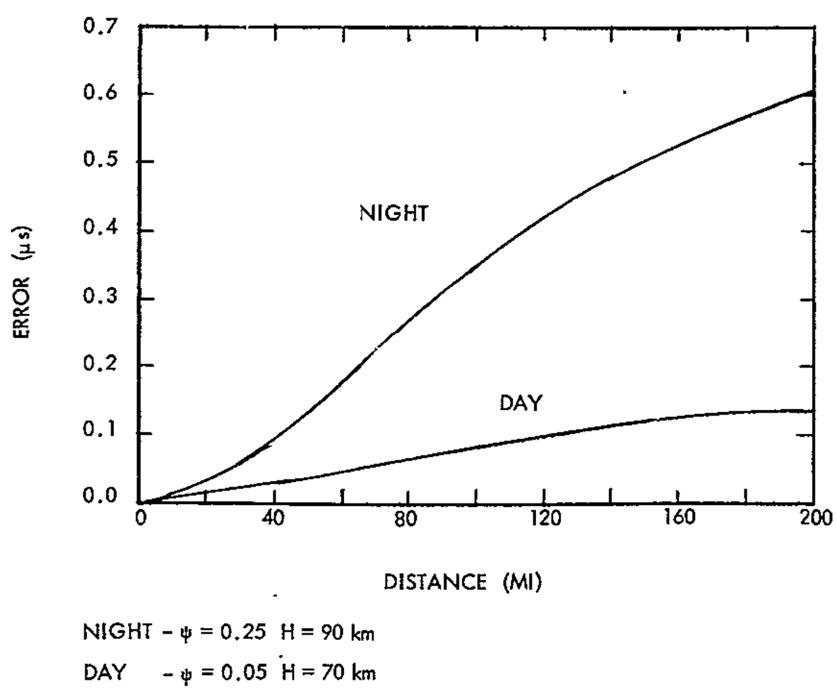


Figure F-6. Sky Wave Error

The error growth in Figure F-6 is approximately

$\delta t = 0.0008D \ \mu s$ day

$\delta t = 0.0033D \ \mu s$ night

F.2.3.4.3 Resolution Error and Receiver Noise

The state of the art in the phase detection of phase locked loops is about one part per thousand. Thus a conservative value of resolution error and set noise is

$\sigma_t \approx 0.02 \mu s$

F.2.3.4.4 Velocity of Propagation

The velocity of propagation of the LF ground wave is a function of several parameters. Johler et al (Ref. 86) have presented theoretical calculations for the magnitude of the phase error due to

(1) distance from the source
(2) atmospheric refraction
(3) different surface conductivities

The authors use a time correction tc which should be subtracted from the predicted time measurement to yield the correct propagation time at a distance D.

For typical land conductivities (σ = .005 mho/m) and propagation distances of up to 200 mi

$tc = 1.23 \pm .87 \mu s$

The gradient of the correction is

$$\frac{\Delta tc}{\Delta D} \approx \begin{cases} .009\ \mu s/\text{mile @D} = 10 \text{ miles} \\ .002\ \mu s/\text{mile @D} = 200 \text{ miles} \end{cases}$$

Hence the assumption of a constant velocity of propagation (hence a constant gradient of tc) is in error. Scott [Ref 88] has obtained excellent agreement with the theoretical values of tc as calculated from the formulation of Johler et al [Ref 86] by using a least squares fit of the form

$$tc = \frac{A}{D} + B + CD \qquad (13)$$

where the constants A, B and C change with conductivity and altitude.

The knowledge of what value to use for conductivity is also important in determining which value of tc to use. If a path is assumed to be of conductivity $\sigma = 0.005$ and the actual conductivity is $\sigma = 0.002$ the resulting time error at 200 miles is 0.93μs. This effect can produce large predictability errors in the time difference measurements. Propagation paths of mixed conductivity are more likely to occur than that of constant conductivity. An error of 0.4 μs for the velocity of propagation was assumed for these mixed paths.

Atmospheric refraction affects the velocity of propagation to a small extent as does the vertical lapse rate of the atmosphere. These effects are small, however, when compared with conductivity variations.

F.2.3.4.5 Altitude Effects

As an aircraft approaches a transmitter two phenomenon occur. First, the slant range from the source to the aircraft begins to deviate from the ground range. The second effect is that the receiver begins to receive signals from the near field of the source. Both effects can produce large time anomalies from the typical model of the phase fronts of the signals. Hence it is desirable to operate at least a few wavelengths removed from the transmitters. At altitudes less than 25,000 ft., which include terminal area altitudes, altitude compensation is innecessary. At 25,000 ft. a 10σ increase in the ground-level error will result. The error is within the 1975-85 accuracy requirement.

F.2.3.4.6 Phase Anomalies

Phase anomalies have been domonstrated theoretically by Johler and Berry [Ref 89], Wait [Ref 90] and several other theoreticians. Phase anomalies due to conductivity boundaries have been observed by Williams [Ref 87] and others. Anomalies due to terrain features such as mountains have been observed by O'Day [Ref 91].

Johler and Berry simulated the effect of a gaussian shaped ridge upon the phase and amplitude of the LF ground wave. Their theoretical work showed sudden deviations of approximately 0.3 μs near a 0.5 km ridge. This effect was also apparent at an altitude of 10 km. Deviations of over 1.5μs were calculated for a ridge of height 2.5 km.

Wait's paper describes the phase variation upon crossing a conductivity boundary. Wait's curve for $q = 0.03$ is typical of a land-sea boundary at 100 kc. This curve indicated a deviation of 0.15 μs at a distance of 4.7 mi past the boundary. The phase anomalies are not entirely local effects.

O'Day observed phase variations of Decca signals in an Arizona field test. Phase variations of 0.1 to 0.25 lanes (≈ .12 to .30 μs) are indicated over broad areas of the test region. A very interesting demonstration of the phase variation is shown by the data taken along the

Hachita Road. The phase deviation changed by as much as 0.15 lanes in four miles which indicates some high frequency error components. Since the principle use of LF navigation has been over water, very little experimental work has been documented as to the magnitude and frequency spectrum of these errors. Volz [Ref 92] has demonstrated that the Arizona data of O'Day's exhibited spatial correlation tendencies. Thus there is some experimental evidence that error reduction is possible through the use of these spatial correlation properties. However, data is very scant in this field, and more experimental work is necessary both in coastal and mountainous areas and in urban and rural areas to validate this hypothesis. A description of how such error reduction techniques may be applied to TD systems is described in Section F.2.4.

F.2.3.4.7 Station Location and Chain Operation Errors

Chain synchronization errors can be made small by using a stationary monitor station to record TD readings. The TD measurements are compared to a standard, and corrections are sent to the transmitters. Some degradation can be expected at night when skywave contamination reduces the system repeatability. Since the stations are separated from 50 to 100 miles, a satellite survey accuracy of 10 parts per million yields an error of only 5 feet.

F.2.3.4.8 Ellipsoidal Earth Corrections

Simple correction terms can yield moderately accurate distance ($\approx$ .1 mile) and azimuth computations for distances on the ellipsoid of up to 200 miles. More sophisticated solutions are possible for the users with sufficient computer capability.

F.2.3.4.9 Summary of LF/CW System Errors

Estimates of time error, time difference error, and position fix errors for several sources of LF/CW system errors are presented in Table F-II. The position fix errors are given for two typical points.

TABLE F-II
LF/CW SYSTEM ERRORS

	Time (μs)	Time Diff (μs)	Location 1 (ft)	Location 2 (ft)
REPEATABILITY ERRORS				
Resolution and Receiver Noise	0.02	0.028	42	126
Atmospheric Noise - 99%	0.0001D	0.0001D	21	126
Aircraft Maneuvers - 0.5g	0.01g	0.014g	11	32
Skywave Contamination - Day	0.0008D	0.0011D	168	1008
Skywave Contamination - Night	0.0033D	0.0046D	693	4158
Atmospheric Refraction	0.01	0.014	21	63
Chain Synchronization	0.01	0.014	21	63
PREDICTABILITY ERRORS				
Velocity of Propagation	0.4	0.56	840	2520
Aircraft Altitude (D > 10)	$2.5H^2/D$	$3.5H^2/D$	$52.5H^2$	$78.8H^2$
Terrain Anomalies	0.3	0.42	630	1890
Conductivity Variations	0.15	0.21	315	945
Oblate Spheroid	0.0001D	0.0001D	21	126
RELATIVE ERROR GRADIENTS				
Velocity of Propagation	0.04/mile	0.056/mile		
Terrain Anomalies	0.03/mile	0.042/mile		
Conductivity Variations	0.015/mile	0.021/mile		
Oblate Spheroid	0.0001/mile	0.0001/mile		
POSITION ERRORS: REPEATABILITY - Day			177	1028
Night			695	4163
PREDICTABILITY			1096	3291
TOTAL - Day			1110	3448
Night			1298	5307

D = Average Distance to Transmitter in Miles
g = Aircraft Acceleration in g's
H = Aircraft Altitude in Miles

in the primary coverage area. The higher accuracy figure is for a point in the center of the coverage pattern, and the lower accuracy figure is for a point in the fringe of the coverage area.

F.2.3.5 LF SYSTEM/PULSE RECEIVER

The CW receiver was limited in range by skywave contamination. The range of LF systems can be extended by a factor of five if pulse signals are transmitted. The skywave signal path is several miles longer than the ground wave path. At 1,000 miles the skywave path is approximately 11 miles (60 μs) longer than the ground wave path. Thus, if measurements are made upon the pulse before the arrival of the skywave, the results contain no skywave contamination. Loran C uses a sampling point that is 30 μs from the beginning of the pulse. The sampling process yields a much lower average power input into the receiver. In order to offset this problem, the peak radiated power of the transmitters are very high. Some Loran C transmitters utilize 4 MW transmitters. This may not be a practical radiated power for transmitters in populated areas. Antenna nonlinearities produce harmonics of the LF signal which could interfere with the operation of users of these harmonic frequencies. Nevertheless, a 4 MW transmitter is assumed in the following analysis.

F.2.3.5.1 Atmospheric Noise and Dynamic Errors

The following pulse PF system is considered.

System: LF-Pulsed time difference with phase measurements upon the carrier frequency

Frequency: 100 kHz

Power: 4 MW Radiated power

Range: 1000 miles over land

Pulse Repetition Rate: 100 pulses/sec

Atmospheric Noise: 13.7 μv/m in a 1Hz bandwidth (hourly average noise exceeded only 1% of the time in the New York City area during the noisiest four hour period of the year - 0000-0400 hours, summer night [Ref 80]

Signal Field Strength: 926 μv/m at 1000 miles [Ref 86]

Utilizing the atmospheric noise Equation (55) and the dynamic error Equation (62) from Section 2.4.2.2 , the receiver constant B is

$B = .574$ rad/sec

and the corresponding time error at the design point is

$\delta t = 0.20\ \mu s$

The error is acceptable for the 4 MW transmitter. If a 250 kW transmitter is used, the design error increases by a factor of 3. At this point, the error is marginal and rate aiding from an external source is necessary.

F.2.3.5.2 Skywave Contamination

The use of the pulse signal virtually eliminates skywave contamination with one exception. When an operator enters a service area, it is possible to acquire and track the skywave signal because the field strength of the skywave exceeds the ground wave. Thus proper safeguards to prevent this possible event must be incorporated in the receiver design.

F.2.3.5.3 Other LF Error Sources

The sources of error for LF pulsed systems are essentially the same as those for the LF/CW system. The magnitudes of the errors may vary somewhat from the CW errors, however, due to the longer range of the pulse system These errors are presented in Tables F-III and F-IV.

TABLE F-III
LF PULSE SYSTEM ERRORS
(4 MW TRANSMITTER)

	Time (μs)	Time Diff (μs)	Location 1 (ft)	Location 2 (ft)
REPEATABILITY ERRORS				
Resolution and Receiver Noise	0.02	0.028	42	126
Atmospheric Noise - 99% - Loc. 1	0.024	0.034	52	
Atmospheric Noise - 99% - Loc. 2	0.20	0.283		1274
Aircraft Maneuvers - 0.5g	0.05	0.071	107	320
Skywave Contamination - Day	-	-	-	-
Skywave Contamination - Night	-	-	-	-
Atmospheric Refraction	0.01	0.014	21	63
Chain Synchronization	0.01	0.014	21	63
PREDICTABILITY ERRORS				
Velocity of Propagation	0.40	0.566	849	2547
Aircraft Altitude (D > 10)	$2.5H^2/D$	$3.5H^2/D$		
Terrain Anomalies	0.30	0.424	636	1908
Conductivity Variations	0.15	0.212	318	954
Oblate Spheroid	0.0001D	0.0001D	105	630
RELATIVE ERROR GRADIENTS				
Velocity of Propagation	0.04/mile	0.057/mile		
Terrain Anomalies	0.03/mile	0.042/mile		
Conductivity Variations	0.015/mile	0.021/mile		
Oblate Spheroid	0.0001/mile	0.0001/mile		
POSITION ERRORS: REPEATABILITY - Day			130	1323
Night			130	1323
PREDICTABILITY			1112	3382
TOTAL - Day			1120	3632
Night			1120	3632

g = Aircraft Acceleration in g's
D = Average Distance to Source in Miles
H = Aircraft Altitude in Miles

A slight deviation from the above statement may be made for terrain anomalies. In the same manner, as the pulse receiver discriminates against skywave, it can discriminate against the effects of terrain anomalies whose paths are such that their time delay exceeds the sampling point time on the pulse. Such a region can be described by an ellipse with the transmitter and user as foci. All anomalies outside of this ellipse have no influence upon the TD measurement.

TABLE F-IV
LF PULSE SYSTEM ERRORS
(250 KW TRANSMITTER)

	Time (μs)	Time Diff (μs)	Location 1 (ft)	Location 2 (ft)
REPEATABILITY ERRORS				
Resolution and Receiver Noise	0.02	0.028	42	126
Atmospheric Noise - 99% - Loc. 1	0.096	0.136	204	
Atmospheric Noise - 99% - Loc. 2	0.80	1.132		5094
Aircraft Maneuvers - 0.5g	0.05	0.071	107	320
Skywave Contamination - Day	-	-	-	-
Skywave Contamination - Night	-	-	-	-
Atmospheric Refraction	0.01	0.014	21	63
Chain Synchronization	0.01	0.014	21	63
PREDICTABILITY ERRORS				
Velocity of Propagation	0.40	0.566	849	2547
Aircraft Altitude (D > 10)	$2.5H^2/D$	$3.5H^2/D$		
Terrain Anomalies	0.30	0.424	636	1908
Conductivity Variations	0.15	0.212	318	954
Oblate Spheroid	0.0001D	0.0001D	105	630
RELATIVE ERROR GRADIENTS				
Velocity of Propagation	0.04/mile	0.057/mile		
Terrain Anomalies	0.03/mile	0.042/mile		
Conductivity Variations	0.015/mile	0.021/mile		
Oblate Spheroid	0.0001/mile	0.0001/mile		
POSITION ERRORS: REPEATABILITY - Day			236	5106
Night			236	5106
PREDICTABILITY			1112	3382
TOTAL - Day			1137	6124
Night			1137	6124

g = Aircraft Acceleration in g's
D = Average Distance to Source in Miles
H = Aircraft Altitude in Miles

F.2.4 Time Difference Receiver Equations

F.2.4.1 Receiver Tracking Loop

The signal S(t) received from one transmitter is of the form

$$S(t) = Sp \sin(\omega t + Kd) \qquad (14)$$

where

$S(t)$ = received signal

Sp = peak signal voltage

ω = radian frequency of the transmitted signal

K = ω/c = phase constant

c = velocity of propagation

d = distance from transmitter to receiver

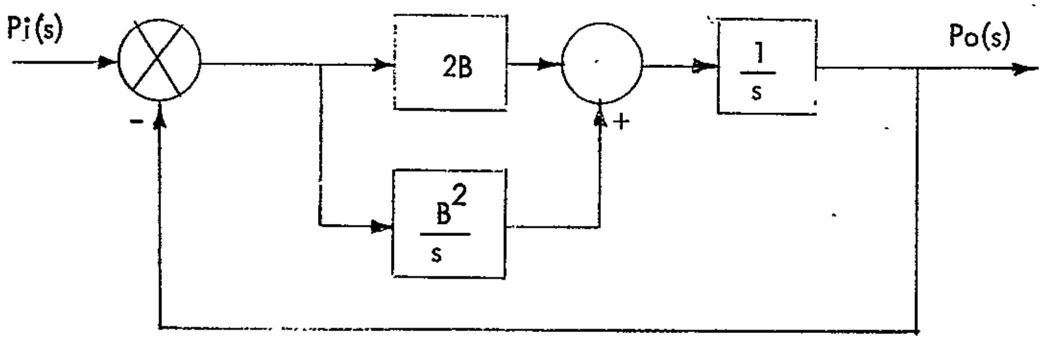
From equation (1) it can be seen that the distance information is contained in the phase of the incoming signal. A common technique for extracting this phase is through the use of a phase locked loop. The transfer function of the phase locked loop can be synthesized from:

1. input signal format and parameters
2. noise environment of the receiver
3. aircraft dynamics

In normal flight an aircraft is flying at a constant velocity. The receiver should have no error due to motion at a constant velocity. From control system theory it is known that a Type 2 feedback control system exhibits this behavior. In addition, the Type 2 system should respond quickly but without oscillations to rapid changes in the input signal. This is achieved by a critically damped phase locked loop. Hence a critically damped Type 2 feedback control system for phase detection of the input signal is selected for analysis.

An analytical representation of a phased locked tracking loop in Laplace operator notation is shown in Figure F-7.

Figure F-7 Phase Locked Tracking Loop



where s = Laplace operator

Pi = phase of the input signal

Po = output of the phase locked loop

B = a receiver constant to be determined

The transfer function of the loop is

$$H(s) = \frac{Po(s)}{Pi(s)} = \frac{2Bs + B^2}{s^2 + 2Bs + B^2} \qquad (15)$$

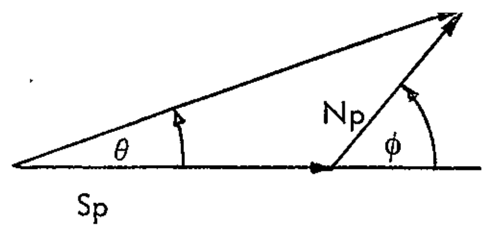
and the error response is

$$Pe(s) = Pi(s) - Po(s) = \frac{s^2 Pi(s)}{(s + B)^2} \qquad (16)$$

F.2.4.2 Receiver Noise Analysis

An analytical model of the degradation in receiver performance due to noise can be constructed from the following relationships. The input signal is given by Equation (14). The quadrature components of the noise signal add to the signal at any instant as shown in Figure F-8.

Figure F-8 Sum of Signal and Noise Inputs



where Sp = peak signal voltage
Np = peak noise voltage
ϕ = random phase of the noise
θ = phase error due to noise

The instantaneous phase error is

$$\theta = \tan^{-1} \left[\frac{Np \sin \phi}{Sp + Np \cos \phi} \right] \tag{17}$$

If $Np/Sp \ll 1$, then (17) can be written

$$\theta \approx \frac{Np \sin \phi}{Sp}$$

Assuming that ϕ is a uniformly distributed random variable in the interval $0 \leq \phi < 2\pi$, the mean phase error $\overline{\theta}$ is zero and the mean square phase error is:

$$\sigma_\theta^2 = \frac{Np^2}{2\, Sp^2} = \frac{N^2}{2\, S^2} \tag{18}$$

where N = rms noise voltage
S = rms signal voltage

In the following sections the noise to signal ratio is computed for a CW receiver and a pulse receiver with the transfer function of Equation 2.

F.2.4.2.1 CW Receiver

The noise to signal ratio at the receiving antenna can be calculated from field strength graphs for signals such as found in Reference 1 and noise field strength predictions as found in Reference 2. The noise to signal ratio at the output of the receiver is related to the input noise to signal ratio by the following analyses.

A linear receiver tracking loop is assumed in figure 1; thus the superposition principle is valid and the signal and noise response of the loop can be calculated separately.

A constant phase signal Kd is applied to the input of the loop. This is an unrealistic input for a moving receiver; however, the receiver response to a dynamic phase input is covered in Section 2.4.1. The steady state error of the receiver can be found from Equation (16) and the final value theorem which states:

$$Pss = \lim_{s \to 0} sPe(s) \qquad (19)$$

where Pss = steady state error

$Pe(s)$ = Laplace transform of the error output

For a constant input Kd

$$Pi(s) = \frac{Kd}{s} \qquad (20)$$

and

$$Pss = 0$$

hence the steady state output Po is Kd as desired.

The noise input N is assumed to be white noise with a spectral density of $\overline{N}^2$ volts^2/Hz, thus the spectral density of the phase error at the input is from (5)

$$S_{\theta i}(\omega) = \frac{\overline{N}^2}{2S^2} \quad \text{radians}^2/\text{Hz} \tag{21}$$

or alternately

$$S_{\theta i}(\omega) = \frac{1}{4\pi} \frac{\overline{N}^2}{S^2} \quad \text{radians}^2/\text{radian/sec} \tag{22}$$

The mean square phase error at the output of the tracking loop can be found by applying an equation from the theory of stocastic processes.

$$\sigma_{\theta o}{}^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{\theta i}(\omega) \, | H(j\omega) |^2 \, d\omega \tag{23}$$

hence from (2) and (6)

$$\sigma_{\theta o}{}^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{\overline{N}^2}{4\pi S^2} \; \frac{4B^2\omega^2 + B^4}{(\omega^2 + B^2)^2} \, d\omega \tag{24}$$

This integral can be evaluated by contour integration. As a result, the mean square phase error is:

$$\sigma_{\theta o}{}^2 \doteq \frac{5}{16\pi} \; \frac{\overline{N}^2 B}{S^2} \tag{25}$$

The rms time error at the output of the tracking loop is

$$\sigma_t = \frac{1}{2\pi f} \; \sigma_\theta = \frac{.0502\sqrt{B}}{f} \left(\frac{\overline{N}^2}{S^2} \right)^{\frac{1}{2}} \tag{26}$$

or equivalently

$$\sigma_t = \frac{.0502\sqrt{B}}{f} \quad \frac{n}{s} \tag{27}$$

where
- σ_t = rms time error (μ s)
- B = receiver constant (rad/sec)
- f = carrier frequency (MHz)
- n = rms noise density field strength ($\mu V/m/Hz^{\frac{1}{2}}$)
- S = rms signal field strength ($\mu V/m$)

F.2.4.2.2 Pulse Receiver Noise Analysis

The following analysis considers a receiver in which one zero crossing of the carrier frequency is sampled during each pulse. Many phase measuring Loran C receivers are of this type. A wide band filter precedes the phase locked loop. This filter has a bandwidth that is sufficiently wide to allow the pulse to pass undistorted but narrow enough to filter all noise outside of the pulse bandwidth. The input signal is of the form

$$S(t) = Sp \sin (\omega t + Kd + \theta) \tag{28}$$

where θ is the phase error due to noise.

The input to the phase locked loop is a series of samples of the phase $Kd + \theta$ at the pulse repetition frequency fp. The mathematical representation of this phenomenon is a series of impulse functions.

$$Pi(t) = \sum_{n=o}^{\infty} (\alpha K d n + \theta n)\, \delta(t - n\gamma) \tag{29}$$

where
- α = proportionality constant
- K = propagation constant

dn	=	distance from transmitter at time tn
γ	=	time between pulses = 1/fp
$\delta(t - n\gamma)$	=	impulse function at time t = n

The output of the phase locked loop is

$$Po(t) = \int H(u)pi(t-u)\,du \tag{30}$$

where h(u) = impulse response of the loop.

Hence the output is

$$Po(t) = \alpha \sum_{n=o}^{\infty} (Kdn + \theta n)\, h(t - n\gamma) \tag{31}$$

Let the receiver remain stationary in position and assume that it has been running for a long period of time so that a steady state output is reached. Using the superposition principle assume that only the signal Kd is present.

$$Ps = \alpha Kd \sum_{n=o}^{\infty} h(n\gamma) \tag{32}$$

The function h(t) is the inverse Laplace transform of the loop transfer function H(s).

Hence

$$h(t) = L^{-1}[H(S)] = B(2 - Bt)e^{-Bt} \tag{33}$$

and

$$Ps = \alpha BKd \sum_{n=o}^{\infty} (2 - nB\gamma)e^{-nB\gamma} \tag{34}$$

The series is of the form

$$Ps = r \sum_{n=o}^{\infty} X - q \sum_{n=o}^{\infty} n\, X^{n} \qquad |X| < 1 \tag{35}$$

where $X = e^{-B\gamma}$ (36)

The first sum is a power series which is uniformly convergent for $|X| < 1$.

$$f(X) = \Sigma X^n = \frac{1}{1 - X} \quad (37)$$

differentiating this series and multiplying by X, the result is

$$X \frac{df}{dX} = \sum_{n=o}^{\infty} n X^n = \frac{X}{(1 - X)^2} \quad (38)$$

Hence (9) becomes

$$Ps = \alpha K d B \left[\frac{2}{1 - e^{-B\gamma}} - \frac{B \; e^{-B\gamma}}{(1 - e^{-B\gamma})^2} \right] \quad (39)$$

for $B\gamma \ll 1$

$$e^{-B\gamma} \approx 1 \quad (40)$$

$$1 - e^{-B\gamma} \approx B\gamma \quad (41)$$

thus

$$Ps \approx \alpha K d \left[\frac{2B}{B\gamma} - \frac{B\gamma}{(B\gamma)^2} \right] \quad (42)$$

$$Ps \approx \frac{\alpha}{\gamma} K d \quad (43)$$

Setting the proportionality constant $\alpha = \gamma$

$$Ps \approx Kd \quad (44)$$

as desired.

Now let the signal $Kd = 0$ and find the noise response of the loop. From (8)

$$Pn = B\gamma \sum_{n=o}^{\infty} \theta i \, (2 - nB\gamma) e^{-nB\gamma} \quad (45)$$

Assume that the θi are independent with zero mean.

$$E(Pn) = 0$$

The mean square error is

$$E(Pn^2) = \sigma_p^2 = (B\gamma)^2 \sum_{n=o}^{\infty} E(\theta i^2)(4 - 4nB\gamma + n^2B^2\gamma^2)e^{-2nB\gamma} \quad (46)$$

$$+ (E(\theta i \theta j) \text{ terms for } i \neq j)$$

Since the θi are independent

$$E(\theta i \theta j) = 0$$

Hence

$$\sigma_p^2 = (B\gamma)^2 \sigma_\theta^2 \sum_{n=o}^{\infty} (4 - 4nB\gamma + n^2B^2\gamma^2)e^{-2nB\gamma} \quad (47)$$

The first two sums in (11) are of the form of (10a) and (10b) with $x = e^{-2B\gamma}$. The third can be obtained from differentiating (10b) and multiplying by X.

$$X \frac{d}{dX}\left[\frac{f(X)}{dX}\right] = \sum_{n=o}^{\infty} n^2X^n = \frac{X + X^2}{(1 - X)^3} \quad (48)$$

thus

$$\sigma_p^2 = (B\gamma)^2\sigma_\theta^2 \left[\frac{4}{(1 - e^{-2B\gamma})} - \frac{4B\ e^{-2B\gamma}}{(1 - e^{-2B\gamma})^2} + \frac{2B^2\gamma^2}{(1 - e^{-2B\gamma})^3}\right] \quad (49)$$

For B $\ll 1$

$$\sigma_p^2 = (B\gamma)^2\sigma_\theta^2 \left[\frac{4}{2B\gamma} - \frac{4B\gamma}{(2B\gamma)^2} + \frac{2B^2\gamma^2}{(2B\gamma)^3}\right] \quad (50)$$

$$\sigma_p^2 = \frac{5}{4}(B\gamma)\sigma_\theta^2 \quad (51)$$

From (5) for small noise to signal ratios

$$\sigma_p^2 = \frac{5}{8}(B\gamma)\frac{N^2}{S^2} \quad (52)$$

The noise power N^2 is proportional to the wide bandwidth filter Bw.

Hence

$$\frac{N^2}{S^2} = \frac{n^2 Bw}{S^2} \tag{53}$$

where
n = rms noise field strength ($\mu V/m/Hz^{\frac{1}{2}}$)
S = rms signal field strength ($\mu V/m$)
Bw = bandwidth of wide band filter (Hz)

Thus the rms phase error is

$$\sigma_p = \frac{5}{8}\sqrt{\frac{B\,Bw}{fc}}\,\frac{n}{S} \tag{54}$$

and the resulting time error is

$$\sigma_t = \frac{.126}{f}\sqrt{\frac{B\,Bw}{fc}}\,\left(\frac{n}{S}\right) \tag{55}$$

where
B = receiver constant (rad/sec)
f = carrier frequency (Hz)
fc = pulse repetition frequency (Hz)

F.2.4.3 Dynamic Errors

In the preceding analyses the input phase signal was assumed to be constant. In this section the steady state errors at the output of the phase locked loop will be determined for a dynamic input. The results are the same for both the CW and pulsed receiver. Thus only the CW receiver analysis is presented.

F.2.4.3.1 Receiver Dynamic Errors

For a receiver that is moving at a constant velocity away from the transmitter the phase signal is

$$Pi(t) = Kvt \tag{56}$$

and the Laplace transform of the input is

$$Pi(s) = \frac{Kv}{s^2} \tag{57}$$

where K = propagation constant

v = aircraft velocity

By the final value theorem and equation (3) the steady state error is

$$Pss = \lim_{s \to 0} s\,E(s) = \lim_{s \to 0} s\left(\frac{Kv}{s^2}\right)\frac{s^2}{(s+B)^2} = 0 \tag{58}$$

where Pss = steady state phase error.

Thus there is no steady state error in the loop for an aircraft flying at a constant velocity toward or away from a transmitter.

If the aircraft is accelerating directly away from the transmitter the input phase is

$$Pi(t) = \frac{Kat^2}{2} \tag{59}$$

and

$$Pi(s) = \frac{Ka}{s^3} \tag{60}$$

where a = aircraft acceleration.

Again using (3) and the final value theorem

$$Pss = \lim_{s \to 0} s\left(\frac{Ka}{s^3}\right)\frac{s^2}{(s+B)^2} = \frac{Ka}{B^2} \tag{61}$$

The steady state error in time is

$$\delta t = \frac{Pss}{2\pi f} = \frac{a}{cB^2} \tag{62}$$

where δt = steady state time error (μ s)

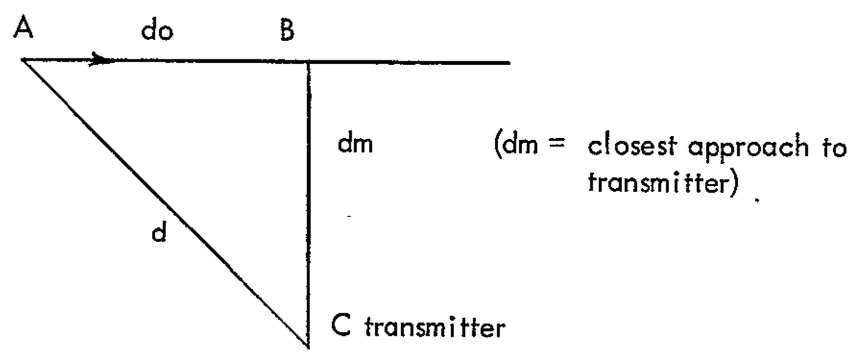
a = acceleration of the aircraft (m/sec^2)

c = velocity of light = 300 m/μ s

B = receiver constant (rad/sec)

In this analysis it has been assumed that the aircraft is either flying toward or away from a single transmitter. In reality an aircraft cannot fly toward or from all transmitters. The motion of the aircraft flying at a constant velocity in some direction other than a radial to the transmitter produces an angular acceleration of the aircraft with respect to the transmitter. This can be shown in the following analysis.

Figure F-9 Aircraft Flight Path



Referring to Fig. F-9, let the aircraft be at point A at time = 0 and flying toward B at a velocity v. Hence the distance d can be expressed as a function of time as

$$d^2 = dm^2 + (do - vt)^2 \qquad (63)$$

It is desired to find the maximum acceleration of d toward the transmitter at C.

$$d\dot{d} = -v(do - vt)$$
$$d\ddot{d} + \dot{d}^2 = v^2 \qquad (64)$$
$$d\dddot{d} + 3\dot{d}\ddot{d} = 0$$

The maximum acceleration occurs when d = 0. From the equation for d it is obvious that either $\ddot{d}$ or $\dot{d}$ have to be zero for this to occur. However, if $\ddot{d}$ = 0 this is certainly not a maximum acceleration. Thus, for $\dot{d}$ = 0 the side of the triangle AB = do - nt = 0 and d = dm. Hence

$$\dot{d}\ max = \frac{v^2}{dm} \tag{65}$$

Thus a high speed aircraft that flies close to a hyperbolic transmitter can experience large time errors due to the angular acceleration of the aircraft with respect to the transmitter. This error is

$$\delta t = \frac{v^2}{dm\, c B^2} \tag{66}$$

where

δt = time error (μ s)

dm = distance of closest approach to the transmitter (km)

v = velocity of aircraft (km/sec)

c = speed of light (0.3 km/μ s)

B = receiver constant (rad/sec)

F.3 DIFFERENTIAL TIME DIFFERENCE SYSTEM

The analyses of Section F.2 indicate that the predictability errors exceed the repeatability errors by a substantial amount. A calibration of the TD system at known locations in the coverage area could significantly reduce the predictability error content of the total error in position. An analysis of the error improvement as a result of applying a calibration procedure is presented in Section F.3.3.

An operational application of such a system could provide improved time difference accuracy in the vicinity of a terminal. A signal flow diagram of a candidate system is shown in Figure F-10.

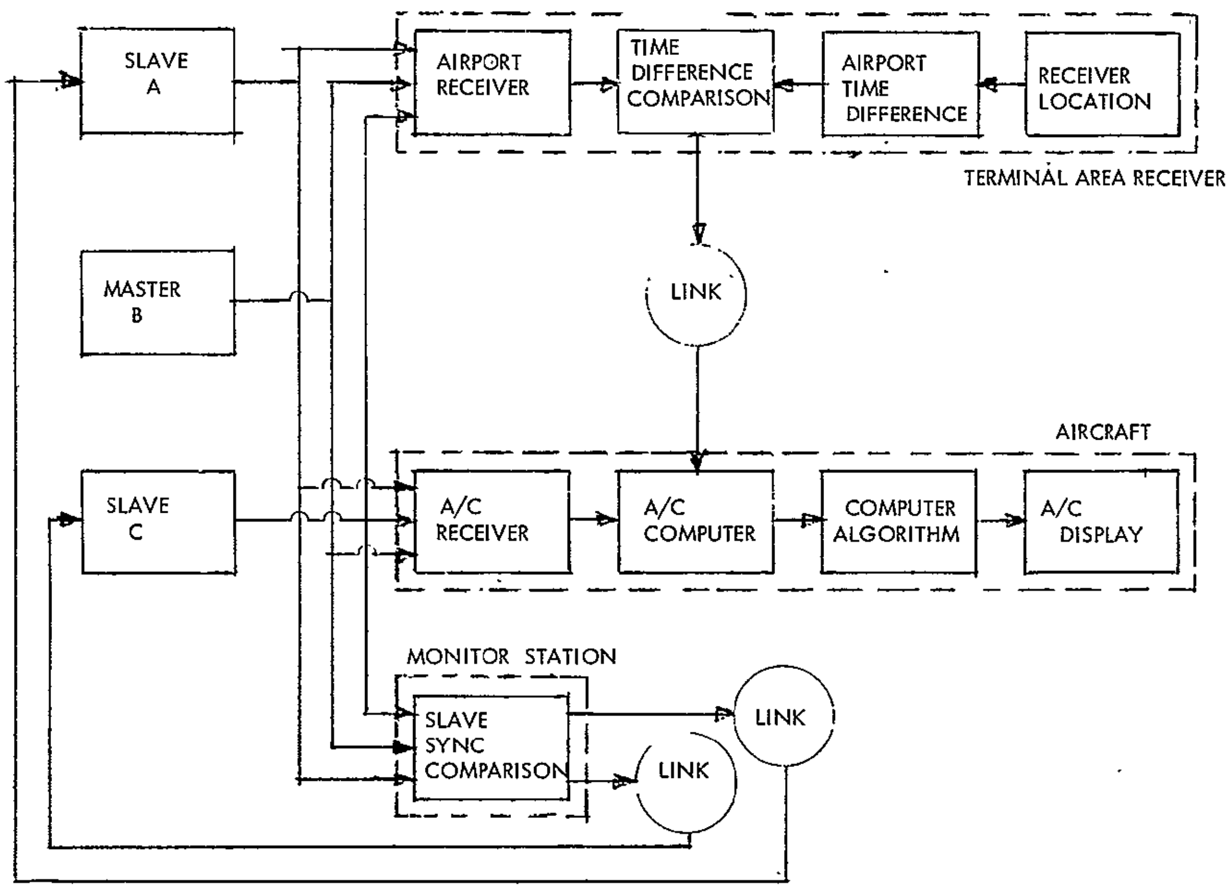


Figure F-10. Differential Time Difference System

The basic TD system is utilized in the nominal operating mode by the user aircraft. The TD signals are also received by a stationary terminal area receiver. The received time differences are then compared to a standard pair of time differences as derived from the receiver location and the propagation model. The difference of the observed measurements from the standard measurements are then a differential time difference (DTD). The DTDs are then sent to the aircraft via a communication link, whereupon they are decoded and added to the observed readings on the aircraft.

F.3.1 Merits of DTD Systems

The basic function of the DTD system is to eliminate or substantially reduce the error in a time difference system. The DTD system performs this function without interfering with the operation of the basic TD system. Thus all the operational advantages of a TD system are retained, and increased accuracy is achieved for highly correlated errors as demonstrated in Section F.3.3.

F.3.2 Drawbacks of DTD Systems

The use of a DTD system does not come without penalty, however. These penalties are:

(1) uncorrelated errors are increased
(2) more equipment is necessary
(3) location of terminal area receiver can increase error
(4) increased accuracy in local area only

The analysis in Appendix F, Section F.3.3.1, demonstrates that there is no reduction in the DTD system error from the TD unless the correlation exceeds 0.5 and, in fact, if all errors are uncorrelated, the error increases by 41%. Thus the correlation of errors is very important. The correlation coefficient in Section F.3.3. is the spatial autocorrelation function of the TD errors. It is analogous to the time autocorrelation function found in the theory of stochastic processes. Its mathematical definition is in normalized form

$$\rho(d) = \frac{E[T(do)\, T(do + d)]}{E[T(do)^2]} \tag{67}$$

where T = time measurement

do = calibration point

d = distance from do

and E represents averaging.

The DTD system requires additional equipment to operate. All of the nominal TD equipment is used plus the following equipment for each installation:

(1) ground based TD receiver

(2) ground support equipment

(3) TD comparison and digitizer

(4) data link

In addition, the user aircraft that has an onboard computer must have receiving equipment to receive the DTD signals and incorporate the signals into his PF solution. No difference in operating procedure or equipment is required for a user who is obtaining his navigation data from a ground based computer and data link. The ground computer inserts the DTD signal into this user's PF solution.

If the terminal area receiver is located near a phase anomaly, a negative value of the spatial correlation function may occur. This would increase rather than reduce errors. Thus careful calibration of the ground based site is required.

The DTD concept will usually produce error reduction in a local area only. Experience with Differential Omega has indicated propagation errors are correlated at ranges of 130 nmi [Ref 82]. Volz [Ref 92] has produced some results that show that phase anomalies of Decca in a mountainous region are correlated out to a distance of approximately 12.5 km. Errors in the shape of the geoid may be correlated out to a range of several hundred miles.

The following results are based upon the results of Tables F-I thru F-IV and equation (14) from Section F.3.3.The predictability errors are assumed to have the following normalized spatial autocorrelation function:

$$\rho(d) = 1 - d/do \quad \text{for } d \leq do \qquad (68)$$

$$\quad = 0 \quad \text{for } d > do$$

where

$$do = \begin{cases} 100 \text{ miles for VLF propagation errors} \\ 10 \text{ miles for LF propagation errors} \\ 1000 \text{ miles for geodetic errors} \end{cases}$$

The DTD system errors are presented in Tables F-V thru F-VIII and shown in Figure F-11 and F-12. The errors are no doubt somewhat greater in most cases than would be expected. However, it should be remembered that "worst case" values for all of the error sources were chosen. In addition, error sources such as transmitter location and oblate earth were included in the error analysis to represent operational problems that could exist at the beginning of a program. Several such error sources could be reduced through operational use leading to a calibration of the system.

Some of the correlation distances used in Tables F-V thru F-VIII are crude estimates. The prime use should be to indicate that the DTD concept is capable of error reduction. Some amount of data is being gathered on Differential Omega which is a DTD system. The results are promising and definitely more optimistic than the errors shown in Table F-V. However, much needed studies and experiments are required before the DTD concept can be validated.

TABLE F-V
DTD/VLF/CW SYSTEM ERROR

	Correlation Distance (mi)	Time Diff (μs)	Location 1* (nmi)	Location 2** (nmi)
REPEATABILITY ERRORS				
Resolution and Receiver Noise	0	0 71	0.12	0.12
Atmospheric Noise - Location 1	0	2.83	0 46	
Atmospheric Noise - Location 2	0	8.49		1.38
Acceleration Error - 1/16g	0	2.12	0 34	0.34
PREDICTABILITY ERRORS				
Diurnal Phase Shift				
Uncorrected	100	0 707/mile	0.114/mile	0 114/mile
Night Corrected	100	0.255/mile	0.041/mile	0.041/mile
Day Corrected	100	0.127/mile	0.021/mile	0.021/mile
Transition Corrected	100	0.170/mile	0.028/mile	0.028/mile
Oblate Earth - Location 1	1000	0.0001/mile	-	-
Oblate Earth - Location 2	1000	0.084	-	-
Station Location	1000	-	-	-
Phase Anomalies (SID)	100	0 707/mile	0.114/mile	0.114/mile
POSITION ERRORS: CONSTANT			0 58	1.42
GRADIENT - No SID (Night)			0.041/mile	0.041/mile
SID			0.120/mile	0.120/mile

*Location 1 - D = 3000 nmi
**Location 2 - D = 6000 nmi

TABLE F-VI
DTD/LF/CW SYSTEM ERROR

	Correlation Distance (mi)	Time Diff (μs)	Location 1* (ft)	Location 2** (ft)
REPEATABILITY ERRORS				
Resolution and Receiver Noise	0	0.028	42	126
Atmospheric Noise - 99%	0	0.0001D	21	126
Aircraft Maneuvers - 1/16g	0	0.001	1 5/mile	4.5
Skywave Contamination - Day	10	0 0011D	16.8/mile	100.8/mile
Skywave Contamination - Night	10	0.0046D	69 0/mile	415.8/mile
Atmospheric Refraction	10	0.014	2.1/mile	6.3/mile
Chain Synchronization	10	0.014	2 1/mile	6.3/mile
PREDICTABILITY ERRORS				
Velocity of Propagation	10	0.566	85.9/mile	254.7/mile
Aircraft Altitude	0	$3.5H^2/D$	0	0
Terrain Anomalies	10	0.42	63.0/mile	189.0/mile
Conductivity Variations	10	0.21	31.5/mile	94.5/mile
Oblate Spheroid	1000	0.0001D	-	-
POSITION ERRORS: CONSTANT			46.98	178 53
GRADIENT - Day			112.389/mile	346.08/mile
Night			130.805/mile	531.51/mile

D = Average Distance to Source in Miles
H = Aircraft Altitude in Miles
* = Center of Coverage Area
** = Fringe of Coverage Area

TABLE F-VII
DTD/LF PULSED SYSTEM ERROR
(4 MW TRANSMITTER)

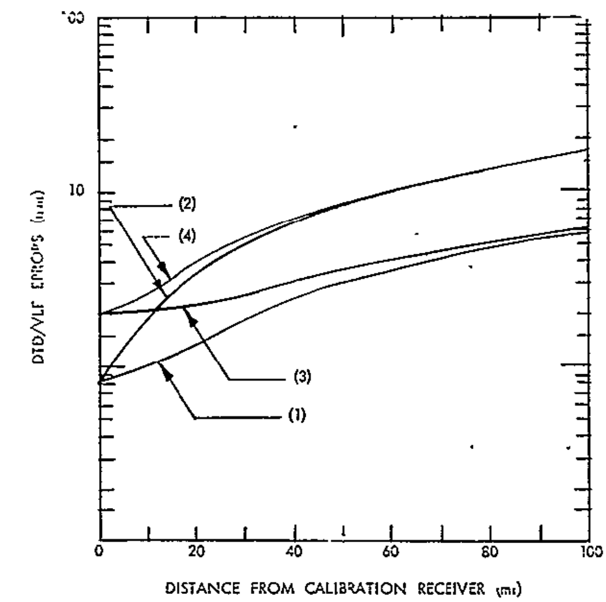
	Correlation Distance (mi)	Time Diff (μs)	Location 1* (ft)	Location 2** (ft)
REPEATABILITY ERRORS				
Resolution and Receiver Noise	0	0.028	42	126
Atmospheric Noise – 99% – Loc. 1	0	0.034	51	
Atmospheric Noise – 99% – Loc. 2	0	0.283		1274
Aircraft Maneuvers – 1/16g	0	0.009	13.5	40.5
Skywave Contamination – Day	10	0	0	0
Skywave Contamination – Night	10	0	0	0
Atmospheric Refraction	10	0.014	2.1/mile	6.3/mile
Chain Synchronization	10	0.014	2.1/mile	6.3/mile
PREDICTABILITY ERRORS				
Velocity of Propagation	10	0.566	84.9/mile	254.7/mile
Aircraft Altitude	0	$3.5H^2/D$	0	0
Terrain Anomalies	10	0.424	63.6/mile	190.8/mile
Conductivity Variations	10	0.212	31.8/mile	95.4/mile
Oblate Spheroid	1000	0.0001D	–	–
POSITION ERRORS: CONSTANT			67.4	1300.8
GRADIENT			110.8/mile	332.7/mile

D = Average Distance to Source in Miles
H = Aircraft Altitude in Miles
* = Center of Coverage Area
** = Fringe of Coverage Area

TABLE VIII
DTD/LF PULSED SYSTEM ERROR
(250 KW TRANSMITTER)

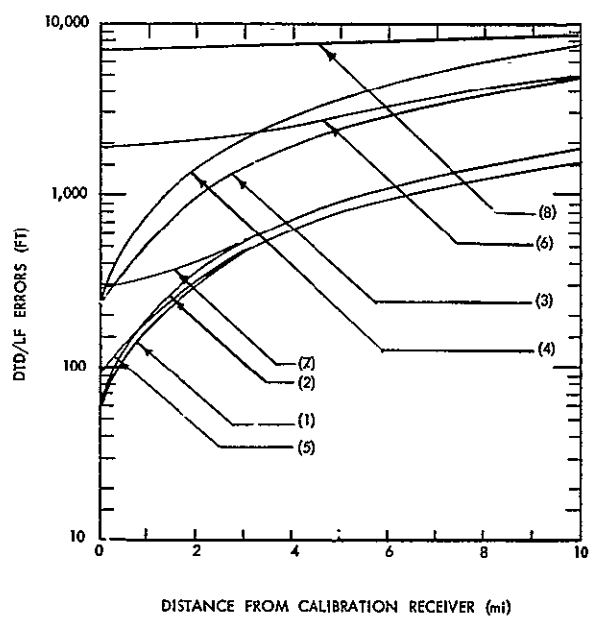
	Correlation Distance (mi)	Time Diff (μs)	Location 1* (ft)	Location 2** (ft)
REPEATABILITY ERRORS				
Resolution and Receiver Noise	0	0.028	42	126
Atmospheric Noise – 99% – Loc 1	0	0.136	204	
Atmospheric Noise – 99% – Loc. 2	0	1.132		5094
Aircraft Maneuvers – 1/16g	0	0.009	13.5	40.5
Skywave Contamination – Day	10	0	0	0
Skywave Contamination – Night	10	0	0	0
Atmospheric Refraction	10	0.014	2.1/mile	6.3/mile
Chain Synchronization	10	0.014	2.1/mile	6.3/mile
PREDICTABILITY ERRORS				
Velocity of Propagation	10	0.566	84 9/mile	254 7/mile
Aircraft Altitude	0	$3.5H^2/D$	0	0
Terrain Anomalies	10	0.424	63.6/mile	190.8/mile
Conductivity Variations	10	0.212	31.8/mile	95.4/mile
Oblate Spheroid	1000	0.0001D	-	-
POSITION ERRORS: CONSTANT			208.7	5095.7
GRADIENT			110.8/mile	332.7/mile

D = Average Distance to Source in Miles
H = Aircraft Altitude in Miles
* = Center of Coverage Area
** = Fringe of Coverage Area



(1) LOCATION 1 NO SID
(2) LOCATION 1 SID
(3) LOCATION 2 NO SID
(4) LOCATION 2 SID

Figure F-11. DTD/VLF System Errors



LF SYSTEMS

(1) LOCATION 1 CW DAY
(2) LOCATION 1 CW NIGHT
(3) LOCATION 2 CW DAY
(4) LOCATION 2 CW NIGHT
(5) LOCATION 1 PULSE 4 MW
(6) LOCATION 2 PULSE 4 MW
(7) LOCATION 1 PULSE 250 KW
(8) LOCATION 2 PULSE 250 KW

Figure F-12. DTD/LF System Errors

F.3.3 Differential Time Difference Error Analysis

F.3.3.1 DTD Error

Let the error in a PF system be

$$dP = GdT$$

dP = position error vector

G = transformation matrix

dT = TD errors

such that at points P_1 and P_2

$$dP_1 = G_1\, dT_1 \tag{69}$$

$$dP_2 = G_2\, dT_2 \tag{70}$$

The differential error is

$$\Delta P = dP_1 - dP_2 = G_1 dT_1 - G_2 dT_2 \tag{71}$$

and the mean square value of the differential error is

$$\begin{aligned} E(\Delta P \Delta P^T)^* = {} & G_1 E(dT_1 dT_1^T) G_1^T \\ & + G_2 E(dT_2 dT_2^T) G_2^T \\ & - G_1 E(dT_1 dT_2^T) G_2^T \\ & - G_2 E(dT_2 dT_2^T) G_1^T \end{aligned} \tag{72}$$

Assume that for P_1 and P_2 close together

$$G_1 = G_2 = G$$

$$E(dT_1 dT_1^T) = E(dT_2 dT_2^T) = \underline{R_T(0)} \tag{73}$$

* Superscript T indicates a transposed matrix.

where $R_T(d)$ = spatial autocorrelation function of the errors at d_0 and $d_0 + d$ .....

assume $R_t(d)$ has two components:

$R_p(d)$ which is the predictability component;

$R_r(d)$ which is the repeatability component;

and further assume

$$R_r(d) = 0 \qquad d \neq 0 \tag{74}$$

$$R_p(d) = \rho(d) R_p(0) \qquad \rho(d) = \text{a scalar} \tag{75}$$

hence the repeatability errors are not correlated as a function of distance.

From the above assumptions, the mean square error of ΔP is:

$$E(\Delta P \Delta P^T) \approx 2G R_r(0) G^T + 2G R_p(0) G^T - 2\rho(d) G R_p(0) G^T \tag{76}$$

If the base vectors for the position error vector are chosen to be orthogonal, the mean square value of the radial error is the trace of the mean square error matrix.

Let Δrms = rms radial error of ΔP

drms = rms radial error of repeatable error

Drms = rms radial error of predictable error

then from (15)

$$\Delta\text{rms}^2 \approx 2\,\text{drms}^2 + 2\,\text{Drms}^2 - 2\rho(d)\,\text{Drms}^2 \tag{77}$$

Now let the predictable error be

$$\text{Drms} = Q\,\text{drms} \tag{78}$$

The total error before applying differential time difference was

$$DDrms^2 = drms^2 + Drms^2 = (1 + Q^2)\, drms^2 \qquad (79)$$

and (16) can be written

$$\Delta rms^2 = (2 + 2\,[\,1 - \rho(d)\,]\,Q^2)\ drms^2 \qquad (80)$$

hence the ratio of the differential time difference error to the original time difference error is

$$\frac{\Delta rms}{DDrms} = \sqrt{\frac{2(1 + [\,1 - \rho(d)\,]\,Q^2)}{1 + Q^2}} \qquad (81)$$

This ratio is plotted in Figure F-13.

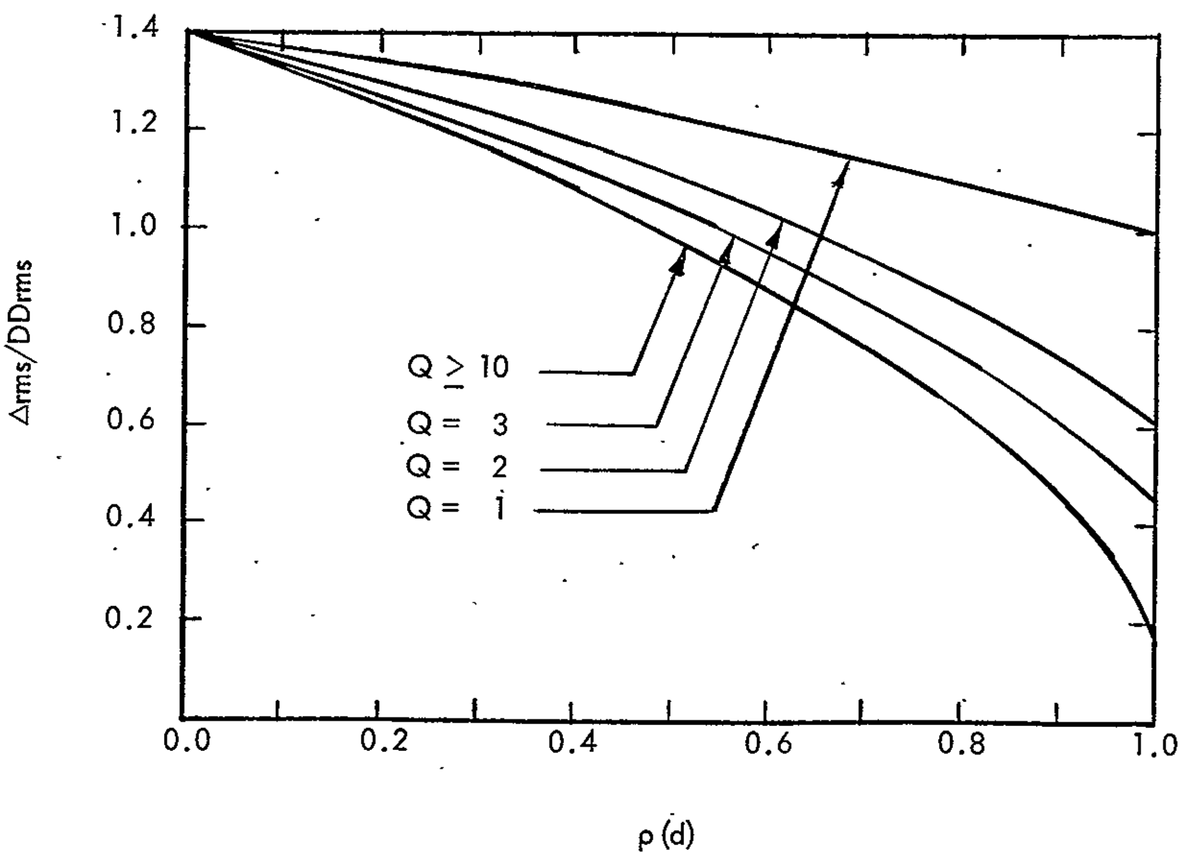


Figure F-13. DTD Improvement

F.4 NAVIGATION SATELLITE SYSTEMS

The feasibility of navigation for ships and position fixing for survey purposes from satellites has been demonstrated by the Navy Navigation Satellite System and Geodetic Secor respectively. The development of a navigation satellite system for aviation has been proposed by several companies. The projected operational features of a time-difference satellite navigation system such as the TRW NAVSTAR concept. [Ref 52] are evaluated with respect to the navigation requirements of the 1975-85 time period.

F.4.1 Summary

Time difference navigation satellite systems have the potential to provide navigation information to aircraft users. The principle merits of navigation satellites are:

(1) Continuous world-wide coverage potential

(2) Coverage at all aircraft altitudes

(3) Minimal propagation errors

(4) High accuracy potential

(5) Ability to meet the operational requirements of the advanced navigation/ATC system of the 1975-85 time period

However, some important deficiencies are apparent in the TD navigation satellite system. Some of the major deficiencies are:

(1) Onboard computer required for "self contained" position determination and guidance computations

(2) Data link required for users with no onboard computer

(3) Ground computers are needed to solve navigation and guidance equations for data link users

(4) Ground based tracking stations are required to derive satellite positions

(5) Expensive airborne receiving equipment required to receive TD signals

F.4.2 Advanced System Requirements

A time difference navigation satellite system similar in concept to the NAVSTAR system as proposed by TRW can satisfy most of the operational and accuracy requirements of an advanced navigation system for use in the 1975-85 time period, subject to one of the following constraints:

(1) An onboard computer is used to solve the position fix equations and derive guidance information from present position and desired track.

(2) A data link is available to transmit satellite TD information to a ground computer for processing into aircraft guidance information from present position and desired track.

The TD navigation satellite and the onboard or ground based computer can satisfy the following requirements:

(1) non-saturable

(2) minimize navigation frequency channels

(3) line-of-sight independent

(4) area coverage

(5) real time operation

(6) all weather capability

(7) time independent

(8) flexible to ATC route structure/vectoring

(9) map reference

(10) common output format

(11) growth oriented

(12) adaptive flight path capability

(13) generate ATC surveillance data

(14) compatible with onboard information needs

In addition, the TD navigation satellite system can satisfy the accuracy requirements for the following flight phase:

(1) climb-out

(2) enroute-low altitude

(3) enroute-high altitude

(4) arrival

(5) descent

(6) approach

The lateral accuracy of a differential time difference satellite navigation system could marginally meet the horizontal accuracy requirements of a Category I and II landing system.

The most outstanding deficiencies of TD navigation satellite systems are the requirements for onboard or ground-based computers, ground-based tracking systems, data links and expensive aircraft receiving equipment.

F.4.3 NAV SAT User Saturation

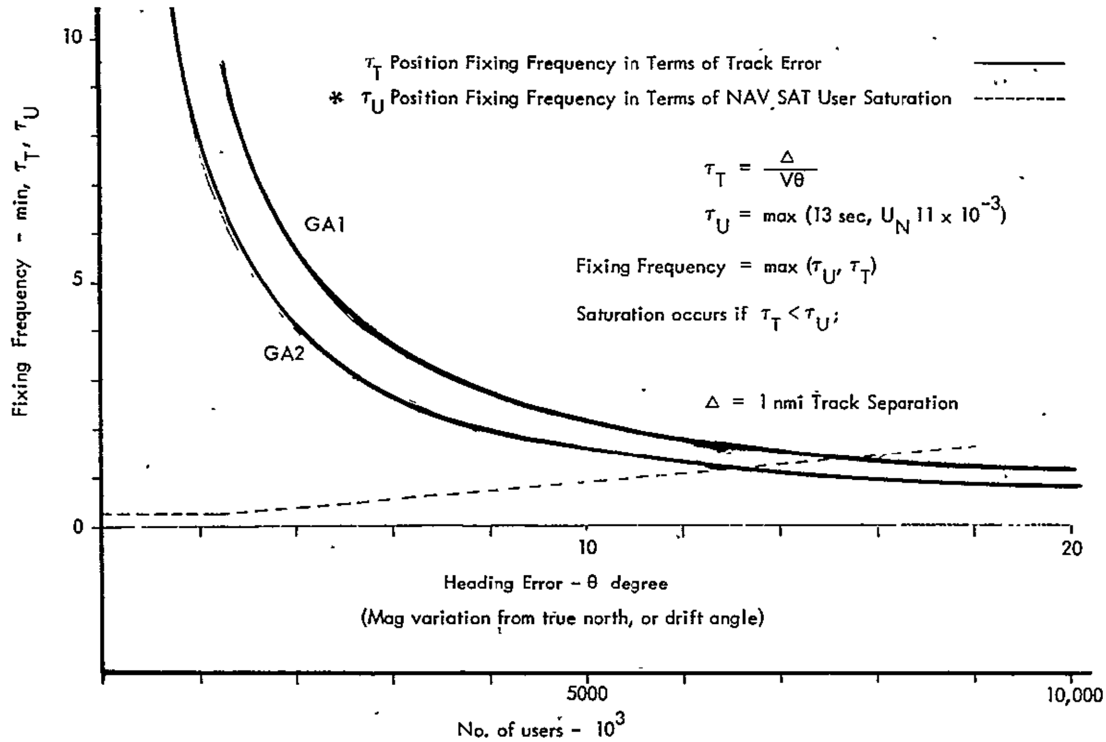
If the navigation-ATC system evaluated in this study were to be implemented using NAV SAT as the external navigation aid, allowance would have to be made through reduction of frequency of update to prevent saturation of the data link. In particular, a requirement for control of all VFR as well as IFR traffic would result in all GA1 and GA2 aircraft, the users who typically have minimal equipment, demanding navigation and communications assistance. This in turn will affect the ability of the system to supply real time surveillance information with which to maintain the aircraft within its assigned space. A parametric relationship has been developed which relates cross track error, frequency of update and potential number of users. Two assumptions were made about the avionics fit of GA aircraft: (1) the GA1 and GA2 do not have accurate dead reckoning subsystems; and (2) the GA1 and GA2 do not have dead reckoning subsystems at all.

Figure F-14 shows the results. For any amount of track keeping error up to 20°, the frequency of fixing, track separation and number of users is given in Table F-15. The results indicate the following:

1 nmi cross track error
48 sec update
4,600 users

If 10° is the maximum heading error, then:

1 nmi cross track error
96 sec update
9,000 users



Track Sepa-ration	Min Fix Freq. Sec	Max Users
10 nmi	480	44,000
1 nmi	48	4,600
0.27 nmi	13	1,200

*Includes all low class users

Figure F-14. NAV SAT System Saturation

F.4.4 Navigation Satellite Systems

Many navigation satellite systems have been proposed by several companies. Several types of position fix measurements utilizing satellites are possible, and an infinite number of orbital configurations for the satellites can be postulated. However, the requirements for the navigation system for the 1975-85 time period are more compatible with some systems than with others.

F.4.4.1 Measurement Types

Several types of measurements for position fixing purposes can be made from satellites. Each measurement defines a surface-of-position (SOP). The intersection of three surfaces of position defines the user's position. One SOP that is commonly used is the user's altitude above mean sea level. This SOP is approximately a sphere about earth's geocenter and the earth radius plus the aircraft's altitude as the radius. Two other SOPs derived from satellite or ground based data can fix the user's position. Some of the more common measurements and their associated SOPs are:

Measurement	SOP
range	sphere
range sum	sphere or ellipsoid of revolution
range difference	hyperboloid of revolution
interferometer angle	cone
plane angle	plane
doppler	cone or hyperboloid of revolution

F.4.4.2 Candidate Advanced Navigation System

The time difference navigation satellite systems possess several of the desirable features for an advanced navigation system. The users can remain passive (i.e. receive signals only), thus reducing the number of frequency channels required for navigation. This is an advantage over the range sum system. Some of the disadvantages of other measurement types are presented. Range systems either require accurate onboard time standards (one part in 10^{11}) or three measurements are required to solve for the clock error. This then becomes very similar to the range difference system. The angular systems require extremely accurate attitude control of the spacecraft (1 μ-rad for 100 ft accuracy at synchronous satellite altitude). The doppler systems require very precise knowledge of the user's velocity vector for accurate position fixing. Accurate position data for the satellite is necessary in addition to all of these above requirements.

The synchronous satellites are a popular choice for proposed navigation systems because the system can be built in modular form starting with only four satellites and because low tracking rates are required. Four satellites could provide the entire continental U. S. with continuous coverage.

If such a system is to achieve world-wide coverage potential, the satellite orbital planes must be inclined with respect to the equator to remove geometric singularities in the equatorial regions of the earth. The satellite subpoints trace the familiar figure eight on the earth's surface.

F.4.4.3 Tracking Requirements

The user must know the position of the satellites in order to produce his position fix. Thus tracking stations and data links are required to furnish the user with satellite position data or an ephemeris of the satellites must be stored aboard the aircraft.

F.4.4.4 NAVSTAR Satellite Navigation Concept

A satellite navigation concept called NAVSTAR which was designed by TRW meets all of the previous requirements. It is used as a design point advanced satellite navigation system. An extensive system description of NAVSTAR is presented in reference 52.

F.4.4.5 Information Requirements

An information flow diagram is shown in Figures F-15 and F-16. Figure F-15 depicts the system for the user with an onboard computer. Figure F-16 pertains to the user with a data link to a ground based computer. L-band signal frequencies are used throughout the system for satellite navigation and communication functions. VHF signals are used for the air to ground data links.

The position fix equations require a computer to convert the time difference measurements into useful guidance information for the pilot. The computer can be programmed to calculate guidance information such as along track and cross track deviation from the flight path, distance and course to the next waypoint and ETA predictions for the waypoints.

F.4.5 Error Sources

The satellite navigation systems have better propagation conditions than do the ground based TD systems. However, the transmitters are non-stationary, which introduces satellite position errors as an error source.

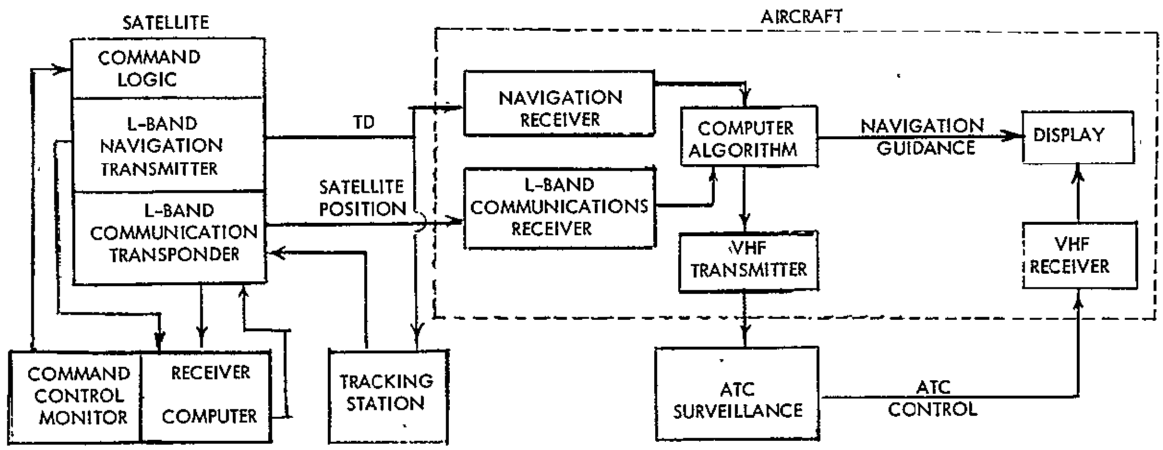


Figure F-15. Signal Flow for User With Onboard Computer

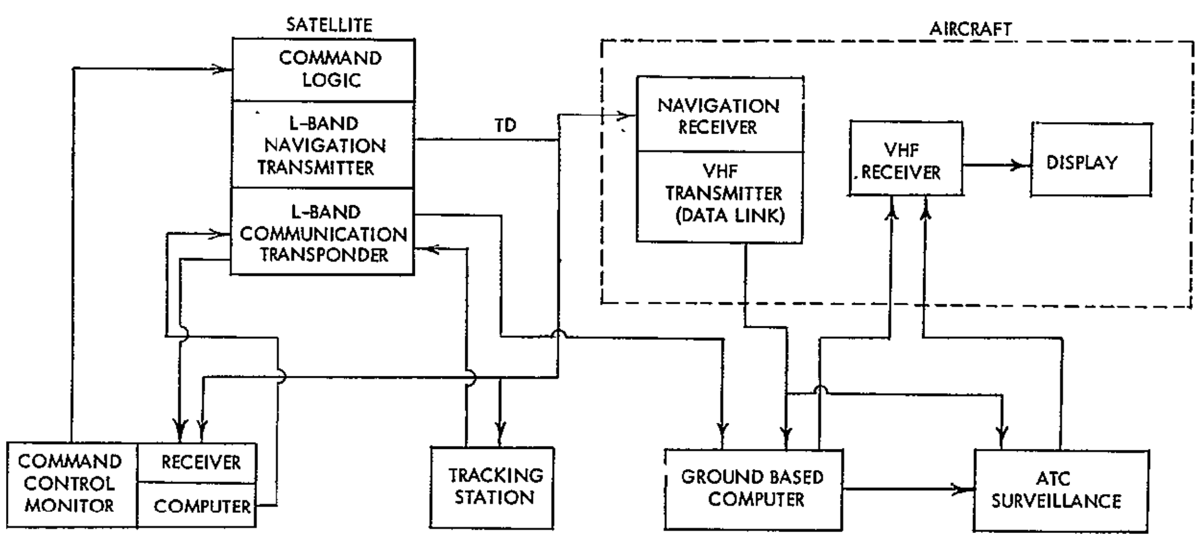


Figure F-16. Signal Flow for User with VHF Data Link

F.4.5.1 Propagation Errors

Navigation satellite systems overcome some propagation anomalies that occur in all ground based navigation and position fixing systems. The satellite signals travel in a line of sight (LOS) path between the satellite and the user so that ground anomalies do not interfere with the propagation. However, some propagation anomalies do occur, such as:

(1) Ionospheric refraction
(2) Atmospheric refraction
(3) Multipath reflection

In order to reduce atmospheric drag and prolong the satellite orbital lifetime for any satellite navigation concept, the satellites are inserted in an orbit that is higher than the earth's atmosphere. Thus the satellite signals have to pierce the earth's ionosphere and troposphere layers. The effect of these layers is to retard the signal, thus producing a slower velocity of propagation of the signal. The ionospheric retardation is inversely proportional to the square of the transmitted signal frequency. Thus higher frequencies are desirable to reduce this phenomena. The TRW-NAVSTAR system error analysis [Ref 52] uses a figure of 56 feet as the uncorrected ionospheric error retardation for an L-band signal at 10° elevation to the earth. The uncorrected tropospheric retardation error is given as 46 feet for a 10° elevation angle.

The multipath error is due to signals being reflected from the earth or other objects and then being received by the antenna. This effect is shown in Figure F-17.

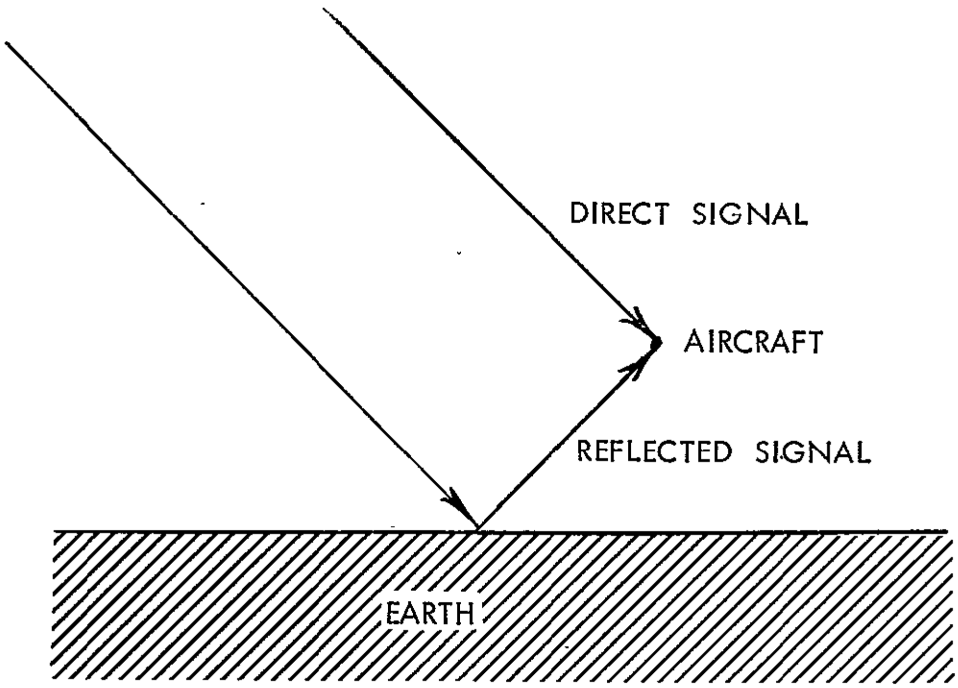


Figure F-17. Multipath Geometry

Multipath reception can be reduced or eliminated by using directive antennas. This is possible for ground tracking stations. However, directive antennas are not practical for the user aircraft due to the necessity of receiving signals from several satellites for all aircraft headings. An error in range of 45 feet was attributed to the multipath effect by TRW.

F.4.5.2 Satellite Position Errors

The use of satellites can significantly reduce the propagation errors, but a new source of error is introduced. The transmitting stations are no longer stationary with respect to the earth. Even the geostationary satellites in the 24-hour equatorial orbits are not truly stationary. Tracking stations are required to locate the satellites' positions. This information must be relayed to the user aircraft if precision position fixing is desired. The TRW study indicates that satellite location errors contribute a 10 to 100 ft increase in the position fixing ability of the NAVSTAR satellite system.

F.4.5.3 Other Error Sources

The receiver and satellite oscillator are two pieces of equipment that can contribute errors to the system. From [52], some of these error sources produce range errors as follows:

(1) Receiver noise (14 ft)

(2) Resolution (10 ft)

(3) Receiver drift (17 ft)

The total rms error contribution for the receiver is less than 25 ft.

The satellite oscillators tend to drift slowly with time. This drift and the drift rate can be calculated from ground station tracking data. A range error of 9.2 feet for oscillator drift error was presented by TRW.

A final error source that is considered is the altitude error of the aircraft. If the surface-of-position of the satellite TD measurements were perpendicular to the earth's surface, the altitude error would not contribute to the position error. However, since these SOPs are hyperboloids and not perpendicular planes, there is a small error introduced into the position fix. The effect is greatest at high latitudes in the NAVSTAR system.

F.4.5.4 Geometric Effects and Total Error

The range uncertainties are magnified due to the geometric effect called GDOP (geometric dilution of precision). A range uncertainty in the NAVSTAR system of 50 ft produces the following results:

Latitude	Position Error (95%)
0-50°	< 250 ft
50-70°	< 600 ft

At higher latitudes than 70° there are a few locations where no PF information is available due to an insufficient number of visible satellites.

F.5 DIFFERENTIAL TIME DIFFERENCE NAV SAT

A study of several relative error calibration schemes was undertaken by TRW in the NAVSTAR system design. One of the very interesting aspects is the mode 2 calibration technique. This concept is very similar to that discussed in the differential time difference discussion in section F.3 . A computer simulation of this technique indicated that the effect of satellite position errors could be eliminated as a source of error over a large area. At the calibration site there were no relative errors due to satellite errors. The relative error 1200 nmi north of the calibration point was only 2 feet greater than the error at that point prior to including satellite position errors. A similar concept was studied by Casserly, Filkins and Hall [Ref73] indicated that more than 85% of the satellite position error could be removed by a compensation scheme at a distance of over 1800 nmi (30° in latitude). These results are quite compatible with the TRW results.

F.6 RADIO-INERTIAL HYBRID SYSTEMS

Radio-inertial hybrid navigation systems incorporate the best features of each subsystem to produce a "best" estimate of present position and to aid the radio system in tracking the time signals with narrow bandwidth phase locked loops. Inertial systems are subject to gyro drift errors and misalignment errors of the inertial platform. The misalignment errors produce undamped oscillations of the platform at the Schuler frequency (84 minute period).

The radio TD system is subject to atmospheric noise errors, dynamic errors and terrain anomaly errors. Narrow tracking loop bandwidths are required to reduce the atmospheric noise errors. However, from equation (13) in Section F.2.4, it can be seen that narrow bandwidths produce large dynamic errors.

The use of a radio-inertial hybrid can permit a dynamically exact system to be designed such that the tracking loop bandwidth of the radio TD system can be made sufficiently narrow to track noisy signals. The resulting position error does not contain acceleration or velocity dependent terms, atmospheric noise errors are made smaller, and tracking in high noise to signal ratio areas is possible.

F.6.1 Summary

A single axis-single channel radio-inertial hybrid navigation system is analyzed and found to be dynamically exact. Thus the performance of the system is independent of the dynamics of the aircraft.

The radio-inertial system removes the ramp error due to gyro drift rate that is present in the pure inertial system. However, oscillating position errors still exist. A radio-inertial combination operating at 100 kHz is analyzed. A pulse repetition frequency of 100 pulses per second and a receiver constant of 0.04 rad/sec are assumed. The range error in the hybrid system for large noise to signal ratios is found to be:

Error Source	Range Error
Atmospheric noise	64 ft
Accelerometer bias (10^{-4}g)	2 ft
Gyro drift rate (0.1°/hr)	8 ft

The oscillatory errors from the accelerometer bias and the gyro drift rate can be damped by providing damping signals from an optimal or suboptimal filter to aid in leveling the inertial platform.

F.6.2 Mathematical Models

Small signal mathematical models are presented for a single axis inertial system and a single channel tracking loop of a TD receiver. The two subsystems are connected to demonstrate the dynamic independence of the output.

F.6.2.1 Inertial System – Single Axis

A single channel representation of the local leveling loop of an inertial platform is shown in Figure F-18. The position output is related to the true position P and the error sources by:

$$Q(s) = P(s) + \frac{\epsilon_a(s)}{s^2 + \Omega^2} - \frac{g\epsilon_g(s)}{s(s^2 + \Omega^2)} \qquad (82)$$

where $\Omega = \sqrt{g/R_o}$ = Schuler frequency (83)

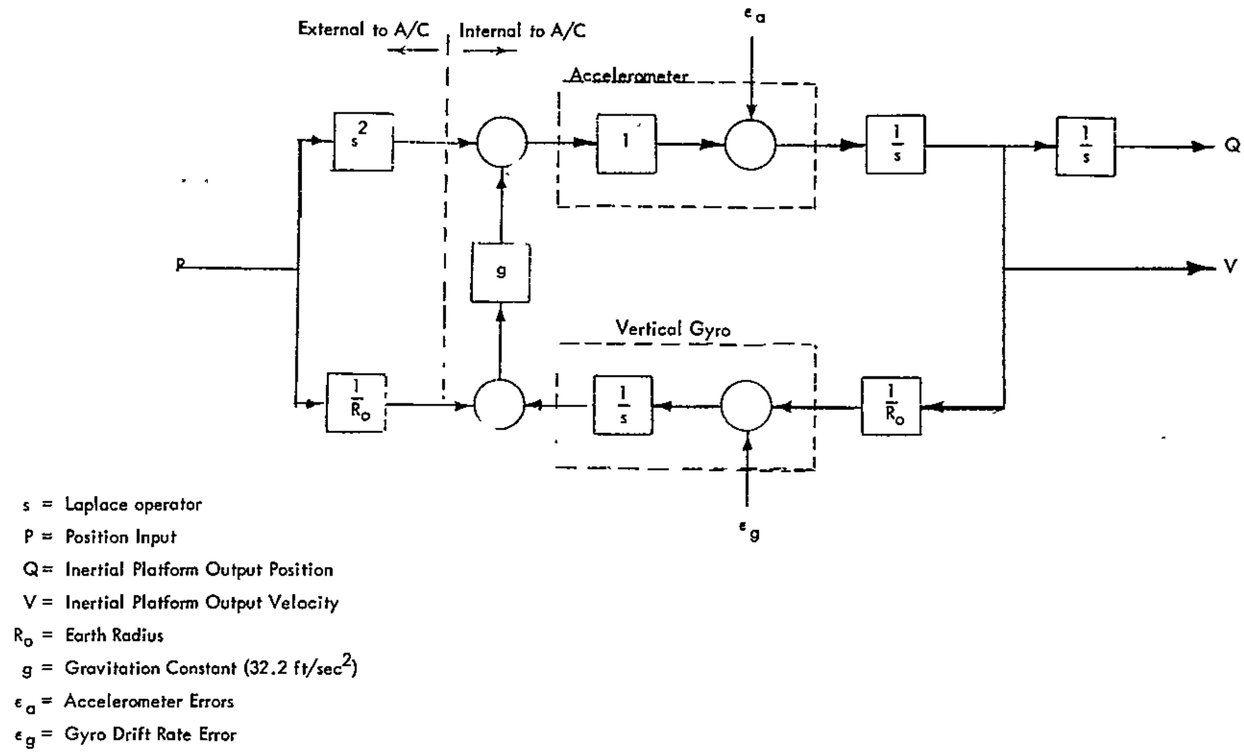


Figure F-18. Single Axis Inertial Platform Position Output

A step input in accelerometer error ϵ_a and the gyro drift rates ϵ_g produce the following output errors:

$$E(t) = Q(t) - P(t) = \frac{\epsilon_a}{\Omega^2} (1 - \cos \Omega t) - \frac{g \epsilon_g}{\Omega^3} (\Omega t - \sin \Omega t) \qquad (84)$$

Thus the position error due to a constant accelerometer error is an undamped oscillation while the error due to a constant drift rate increases linearly with time.

F.6.2.2 TD Receiver - Single Channel

The phase locked tracking loop is analyzed in Section F.2.4. However, the benefits of rate aiding are not discussed in the appendix.

Assume that the phase detection loop of the TD receiver is a critically damped, Type 2 feedback control system with a velocity aid inout from the inertial platform of Figure F-18. Since the radio TD system operates in TD coordinates and the inertial platform operates in local vertical, east, north coordinates, a transformation of coordinates by an onboard computer is assumed. The velocity aided phase locked loop is shown in Figure F-19.

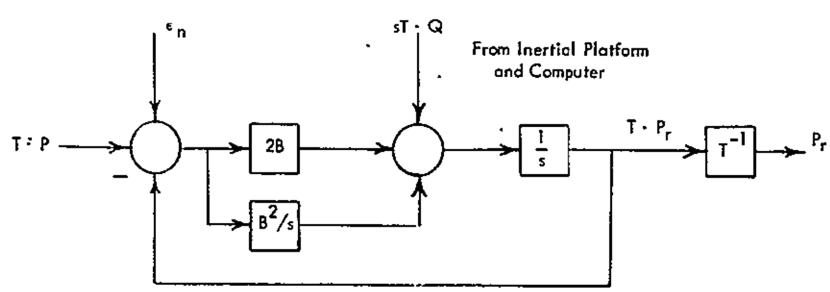
The output of the radio tracking loop is:

$$Pr(s) = P(s) + \epsilon_n(s)\,\frac{(2Bs + B^2)}{(s+B)^2} + \frac{s^2\epsilon_a - gs\epsilon_g}{(s^2+\Omega^2)(s+B)^2} \qquad (85)$$

The atmospheric noise error is random and is often simulated by white noise. In Appendix A the phase error in the phase locked loop is found in equation (11a) for a pulse receiver:

$$\sigma_p^{\ 2} = \frac{5}{4}(B\gamma)\,\sigma_\theta^{\ 2} \qquad (86)$$

For high noise to signal ratios, the phase error θ is a random variable that is uniformly distributed from $-\pi$ to π radians.



s = Laplace operator
T = coordinate transformation matrix
B = receiver constant
P = Position input
P_r = Radio-inertial system output

Figure F-19. Inertially Aided TD Receiver Tracking Loop

In this case...

$$\sigma_\theta = \frac{\pi}{\sqrt{3}} \qquad (87)$$

and the standard deviation of the corresponding range error is

$$\sigma_d = \frac{318}{f} \sqrt{\frac{B}{fc}} \quad \text{ft} \qquad (88)$$

where B = receiver constant

$fc = 1/\gamma$ = pulse repetition frequency

f = carrier frequency (MHz)

For a 100 kHz and a pulse repetition rate of 100 pulses per second

$$\sigma_d = 318\sqrt{B} \quad \text{ft}$$

A contemporary Loran C receiver uses a receiver constant of

$$B = 1/25 \text{ sec}^{-1}$$

hence the resulting range error due to atmospheric noise is

$$\sigma_d = 64 \text{ ft}$$

The accelerometer and gyro drift errors are approximated by step functions of magnitude 10^{-4}g and 0.1°/hr respectively. The response of the radio inertial combination to a step in acceleration error of magnitude ϵ_a is

$$E_a(t) = \frac{\epsilon_a}{B^2} \left\{ \cos \Omega t + \frac{2\Omega}{B} \sin \Omega t - (1 + Bt) e^{-Bt} \right\} \qquad (89)$$

The first two terms are undamped sinusoids and the third term is a decreasing exponential. The peak range error due to accelerometer bias is

$$E_a = \epsilon_a / B^2 = 2 \text{ ft} \qquad (90)$$

A step function in the gyro drift rate error of ϵ_g rad/sec produces a range error of:

$$E_g(t) = \frac{g\epsilon_g}{B^3}\left\{-2\cos\Omega t + \frac{B}{\Omega}\sin\Omega t + (2 + Bt)e^{-Bt}\right\} \tag{91}$$

The peak range error due to gyro drift rate is

$$E_g = \frac{g\epsilon_g}{\Omega B^2} = 8 \text{ ft} \tag{92}$$

F.6.2.3 Other Configurations

The system that was considered in the previous paragraphs exerted no control on the inertial platform. A desirable feature of a hybrid system would permit signals from the radio system to damp the inertial platform. Sophisticated filter analysis can be applied to such a system to design a Kalman-Bucy filter, Wiener filter or a simpler sub-optional filter. The signal flow of such a system is shown in Figure F-20.

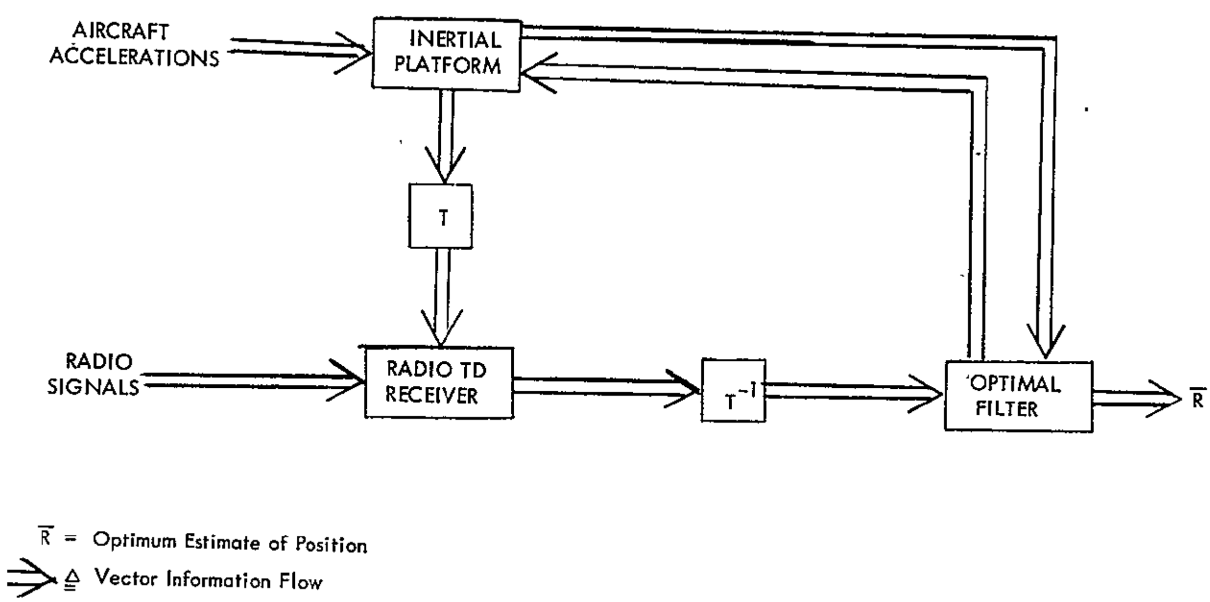


Figure F-20. Signal Flow Diagram for an Optimum Radio-Inertial System

F.7 VOR/DME

The Very High Frequency-Omnidirectional Radio Range/Distance Measuring Equipment (VOR/DME) position finding system is the prime navigation aid for all IFR flights in the United States at the present time. The VOR transmitter permits the user to measure magnetic bearing to the facility and the DME transponder allows the user to measure range to the transponder. The pilot flys along a constant bearing (line of position) with respect to the transmitter; hence the aircraft flies along radials to or from the station. Typically, six to ten radials from the transmitters are used for air routes. All transmitters and some radial intersections from two transmitters are called waypoints in this study and are often given coded names. All IFR air traffic is directed along these air routes; hence this operating procedure leads to congested air routes.

Course line computers have been designed and developed to allow the user to fly off airways and still utilize the VOR/DME signals. Thus the user can select arbitrary waypoints and thereafter fly directly to this waypoint. This permits VOR/DME to be used in an area navigation mode.

Several operating deficiencies and physical limitations of VOR/DME systems are presented in the following sections.

F.7.1 Operational Summary

A summary of operational VOR/DME deficiencies include:

(1) Gaps related to the cone of silence
(2) Inefficient use of airspace
(3) Line of Sight (LOS) limited
(4) Inaccurate position fix information and noncontinuous surveillance information for ATC

F.7.2 VOR/DME Coverage

Frequency protection of VOR/DME facilities can affect operational use of the systems by limiting the guaranteed range of reception.

		Protected Range of Reception
Cat. A	VOR (H)	100 nmi above FL 450
	VOR (H)	130 nmi to FL 450
Cat. B	VOR (L)	40 nmi to FL 180
	VOR (T)	25 nmi to 12,000 ft

Definitions:

VOR (H)	High Altitude Enroute VOR
VOR (L)	Low Altitude Enroute VOR
VOR (T)	Terminal Area VOR

The corresponding DME operational usage is given by the following altitude and interference free distances:

39 nmi to 15,000 ft
78 nmi from 15,000 to 30,000 ft
156 nmi from 30,000 to 75,000 ft

The signal generated by a VOR transmitter can not be received by aircraft in a conical region above the transmitter called the cone of silence. This produces a volume in which no VOR navigation data is available. The cone of silence above a VOR facility is defined by the maximum angle of elevation of signal with respect to the plane of the transmitter and is approximately 40°; the dead zone in nautical miles above the antenna can therefore be defined as $h \cos 40°$ where h = altitude of the aircraft; e.g., for an aircraft at an altitude of 36,000 ft, 6 nm, the radius of the cone of silence would be $6 \cos 40° = 4.6$ nmi

The cone of silence as a function of altitude is tabulated in Table F-IX.

Column 3, VOR Airways, states the diameter of a cross section of the cone with respect to the altitudes indicated. Column 4 indicates the effect of utilizing a course line computer to parallel track at a distance of 5 nmi. At only one altitude, 50,000 ft, does the user enter the cone of silence. If the parallel is set at a distance equal to or greater than 7 nmi, the cone is missed completely for all altitudes up to 50,000 ft.

TABLE F-IX
VOR BLIND ZONES

	Altitude ft	Cone of Silence VOR Airways	Track offset = 5nmi	Track offset ≥ 7 nmi
Low Altitude	5,000	1.25 nmi	0	0
	15,000	3.80 nmi	0	0
High Altitude	25,000	6.30 nmi	0	0
	35,000	8.80 nmi	0	0
	50,000	12.50 nmi	4.9	0

The number of seconds an aircraft would remain within the cone of silence is illustrated below:

CTOL Jet, 35,000 ft (480 kts) = 66 seconds
VTOL at 25,000 ft (450 kts) = 50 seconds
SST at 50,000 ft (1172 kts) = 38 seconds

Terms of reference used with the VOR route structure are:

(1) Maximum Acceptable Altitude (MAA) for jet routes above FL 180

(2) Minimum Enroute Altitude (MEA) for the low altitude enroute structure, 2000 ft MSL to 18,000 ft

(3) Minimum Reception Altitude (MRA) for the low and high altitude enroute structure

(4) Minimum Obstruction Clearance Altitude (MOCA) for low altitude

The MRA is particularly significant to the low altitude VOR route structure and terminal area control. Generally, in the densely populated terminal areas of the 1968 epoch, traffic is radar vectored by the controller utilizing SSR radar data; but if an area navigation system were utilized as the means to flow control, the MEA may become of significance.

F.7.3 Minimum Enroute Altitude

The MEA is selected to provide the pilot with information about safe height above terrain along the airway, and the altitude above which he is assured of receiving a signal free from restrictions to LOS. Use of an Area Navigation System which derives its position information from VOR/DME could be compromised by a lack of knowledge on the part of the operator of the MEA for his area of operation; e.g., an attempt to operate into an airstrip located in a valley could place the receiver in a dead zone. Something of the variability of MEA at randomly selected places in the eastern U. S. is shown below.

For the selected VOR radials in the New York, Cleveland, Philadelphia and Atlanta centers, the sample MEA average was:

New York Area	MEA = 2500 ft
Philadelphia Area	
New Castle VOR	MEA = 2000 ft
West Chester VOR	MEA = 2300 ft
Pottstown VOR	MEA = 2400 ft
Pittsburgh Area	
Harrisburg VOR	MEA = 3700 ft
Johnstown VOR	MEA = 4500 ft
Cleveland VOR	MEA = 3000 ft
Atlanta VOR	MEA = 2700 ft

F.7.4 Inefficient Use of the Available Airspace

A comparison of the potential service which can be made of a VOR airway system to the service which can be provided by an area navigation system produces the following results. In the current route structure, eight to twelve radials per VOR transmitter can be used for the definition of air routes. ATC constraints on cross track separation, altitude separation and number of users per flight level in the cone of silence reduces the number of potential air routes to 4 to 6 user radials.

A convenient method of mathematically identifying the theoretical capacity of the airspace covered by a VOR station is typified by the following expression:

$$\text{Number of Users: } N = 1 + \frac{(R - s)}{V\Delta tr} Nr \qquad (93)$$

$$\text{or } N \leq \frac{(R - s)}{V\Delta t} + 1$$

$$\text{where } \Delta tr \geq Nr\Delta t$$

$$\text{and } \Delta tr \geq \frac{2s}{V},$$

where Nr = number of radials

R = horizontal distance to the station

s = dead zone distance (VOR cone of silence)

V = aircraft speed

Δt = desired longitudinal separation between aircraft

Δtr = a relationship expressing the system saturation constraint for handling traffic at VOR station.

Then let $Nr = 6$, and let $\Delta t = 3$ min.

TABLE F-X
SYSTEM CAPACITY

	Altitude ft	VOR Airways No. of Users/ Point Source	Area Navigation No. of Users/ Area Coverage
Low Altitude	5,000	17 (4)**	20
	15,000	24 (5)	28
High Altitude	25,000	26 (5)	62
	35,000	25 (5)	59
	50,000	11 (2)	26

**Traffic handling constraint, one user in the cone of silence

Assume the following user performance as a function of altitude:

50,000 ft (1100 kts), 18.3 nmi/min

35,000 ft (480 kts), 8 nmi/min

25,000 ft (450 kts), 7.5 nmi/min

15,000 ft (400 kts), 6.6 nmi/min

5,000 ft (180 kts), 3 nmi/min

Separations then are 54.9, 24, 22.5, 19.8 and 9 nmi respectively for the 3 minute time spearation requirement. The limitation of one user in the cone of silence per flight level increases the distance interval by six miles. Placing the latter traffic handling constraint on the system reduces capacity of the system as seen in the parenthesis of Table F-X.

The potential number of users who can be serviced with an area navigation system is determined as follows:

$$N = \left(\frac{1.4R}{2d} + 1\right)\left(\frac{R}{\Delta tV}\right) \text{ where d is lateral track separation} \quad (77)$$

A lateral separation criterion of 5 nmi is assumed for this analysis. While only minor increases in system capacity can be achieved in the low altitude structure, a very substantial payoff is realized from implementation of the area navigation system in the high altitude route structure.

In the current ATC system, traffic operating in the high altitude route structure generally begins transition to a lower altitude when overhead a VOR station unless the aircraft is being vectored by a controller. This procedure significantly impedes flow of traffic, capacity of the system and precipitates uneconomic operation. If a change to an off airways or parallel route system is adopted, provision for climb and descent paths not on the airway should be included in the traffic control planning structure.

It is concluded from the above analysis that:

(1) the present VOR air route system is relatively inefficient in its utilization of the airspace at all altitudes;

(2) the VOR air route system must either use a route structure which constrains the aircraft to a fixed path, or a greater tolerance in position accuracy must be allowed for off-airways operation. In the latter case, it would be necessary for one crew member to be continuously concerned with the navigation task;

(3) implementation of an area navigation system which utilizes computer processed VOR/DME information could significantly increase system capacity and thus bears serious consideration;

(4) off-airways climb and descent paths must be considered.

F.7.5 Frequency Saturation

The VOR stations operate in the VHF band from 112 to 118 MHz with channel separation of 100 kHz. To avoid frequency overlapping in some service regions, the band from 108 to 112 MHz is utilized. The use of 100 kHz channel separation provides 60 channels in the 112-118 MHz band and 40 channels in the 108 to 112 MHz band. This latter set is assigned to ILS localizer freqeencies. Because of the large number of facilities which are required and the limited number of channels which are available, some overlap in frequencies is possible.

F.7.6 Accuracy

Present VOR/DME stations are designed and maintained to provide accuracy of bearing of $\pm$ 2° in azimuth and an error in range not greater than 0.5 nmi of 3% of distance from the facility, whichever is the greater. The generally accepted identification of the error contributors to position determination utilizing VOR/DME inputs is the RSS value of the following components:

DME error + VOR bearing error + slant range correction

DME error = maximum of 3% of DME (slant) range or 0.5 nmi

VOR bearing error = DME range x sin 2° or .034 x DME range

$$\text{slant range error} = R - \left[R^2 - Za^2 \right]^{1/2} \qquad (95)$$

where R = DME (slant) range

Za = aircraft altitude

$$\text{Total Position error} = (\text{DME error})^2 + (.034R)^2 + (R - R^2 Za^2)^{1/2} \qquad (96)$$

TABLE F-XI
VOR/DME POSITION FIX ERROR SUMMARY

	VOR	PE_{VOR}, nmi. (no altitude compensation) Maximum Operational Range	PE_{VOR}, nmi. (no altitude compensation) Near Cone of Silence	PE_{VOR}, nmi. (with altitude compensation) Maximum Range	PE_{VOR}, nmi. (with altitude compensation) Near Cone of Silence
Low Altitude	5,000	1.13	0.53	1.13	0.53
	15,000	1.82	0.84	1.81	0.53
High Altitude	25,000	4.54	1.95	4.53	0.60
	35,000	4.54	1.95	4.53	0.60
	50,000	4.54	1.95	4.53	0.84

These figures show that the error in position of the aircraft relative to the VOR/DME station is principally dependent upon distance from the facility. At high altitude, slant range to ground range compensation is not needed when the aircraft is at a relatively great distance from the facility. However, when operating near the VOR stations, a failure to compensate for the altitude effect becomes a substantial part of the error budget.

While the need for altitude compensation in an area navigation computer system might be questioned for reasons of cost, say for the GA1 and GA2 users, potentially large errors introduced by the airborne data link into the ATC surveillance system could be unacceptable.

F.8 LANDING AIDS SUMMARY

Table F-XII presents a tabular correlation of present landing minima with approach and landing aid systems performance. Conventional landing aids include the

ILS, AILS and Precision Approach Radar (PAR) systems. It will be observed that ILS meets the requirements for CAT II landing; the AILS system, assuming availability of a suitable airborne computer algorithm in the Automatic Flight Control System (AFCS), gives promise of meeting CAT III landing requirements. The accuracy and feasibility of the AILS system is undergoing test at the FAA's NAEFEC facility. The other candidates listed below meet CAT II minima. The DME and Radar Altimeter configuration is recommended for VTOL landing.

TABLE F-XII
WEATHER MINIMUM CONDITIONS - SYSTEM POTENTIAL

	CAT I	CAT II	CAT II	CAT III		
		a	b	a	b	c
RVR, ft.	2600	1600	1200	700	150	0
Min. Decision Height, ft.	200	200	100	0	0	0
ILS	X	X	X	-	-	-
AILS	X	X	X	*	*	*
PAR	X	X	-			
DME & Radar Altimeter	X	X	X			
Ground Based Scanning	X	X	-			

*With onboard processing and/or altimetery data, may be able to derive sufficiently accurate height information to meet IIIc criteria.

F.8.1 Landing Aids

Aids to IFR landing include the following types.

F.8.1.1 ILS

The complete system consists of a VHF localizer (LOC) transmitting and monitor unit (108 MHz to 112 MHz), a UHF glideslope (GS) transmitting and monitor unit (328.6 to 335.4 MHz), and VHF marker beacons (MB). All airports are not equipped with the glideslope mode; some utilize only the localizer channel. However, all FAA certified commercial carrier terminals do incorporate the glideslope localizer and MB transmitters. The coverage geometry of a typical null referenced ILS installation is shown in Figure F-21. This coverage and the system accuracy offer CAT II landing performance. The transmitting system accuracy is:

GS Receiver accuracy:	0.0005° 1σ
GS accuracy:	0.25° 1σ, 0.25 mean, bend tests made at several air terminals disclosed an accuracy of $\pm$ 0.1°. Utilization of vertical arrays and advanced narrow beam radars may permit achievement of the goal of 0.03° or 0.01° in areas where terrain does not create a problem
LOC receiver channel:	0.018° 1σ
LOC:	0.1° σ ; with an improved monitor and an improved waveguide system, 0.01° is looked for.

Stability and accuracy of the ILS beam is affected by the conductivity characteristics of the surrounding terrain. Local conditions such as variations in moisture content of the ground, vegetation and multipath effects created by reflectors such as cars, large aircraft, structural obstructions or new construction can cause significant propagation anomalies. Generally, the glideslope is more sensitive to perturbations in the surrounding environment than is the localizer beam.

The system outputs GS and LOC signals to the aircraft. The airborne system receives and processes the data and presents to the pilot flight path deviation information. Figure F-22 shows the information flow.

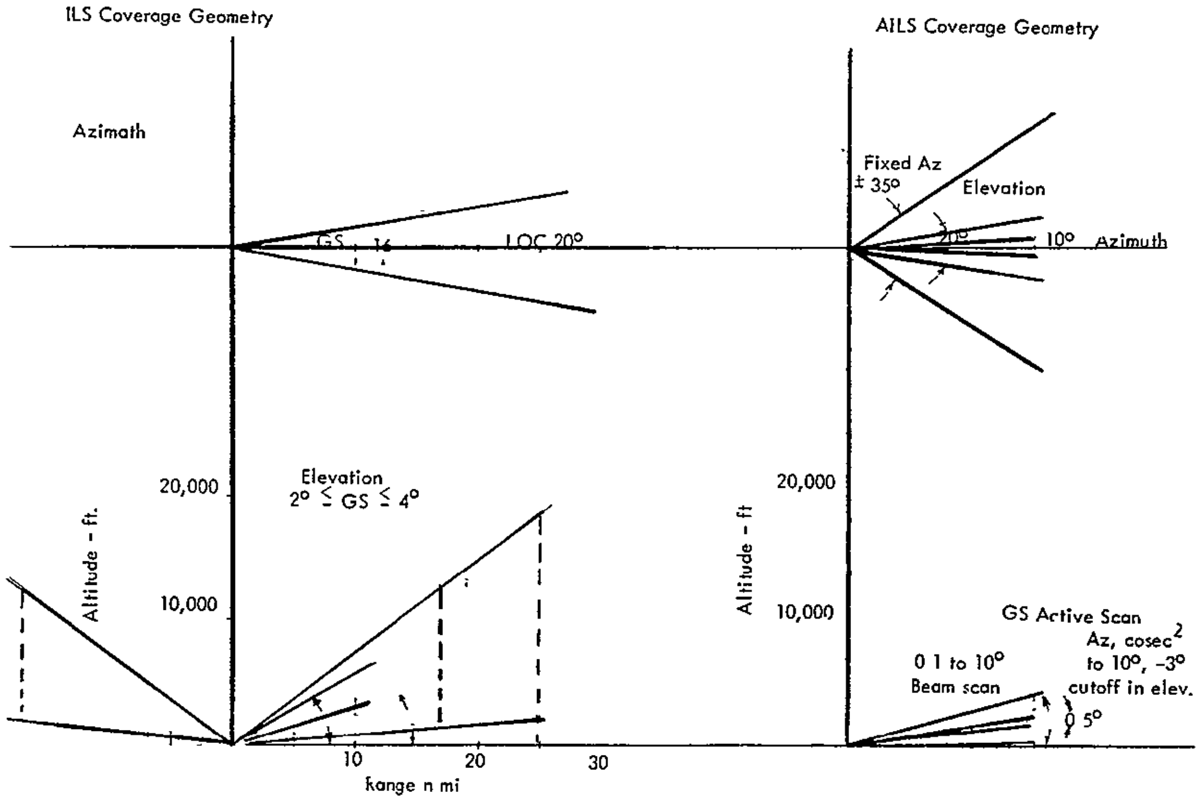


Figure F-21. Landing System Geometry

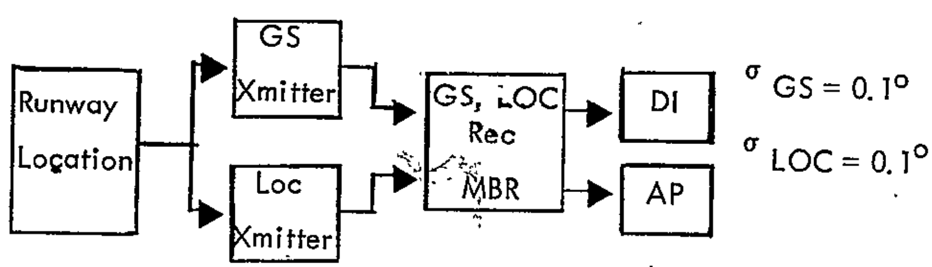


Figure F-22. ILS Information Flow

F.8.1.2 AILS

The Advanced ILS (AILS) system differs significantly from the ILS system. The guidance data to the pilot is derived from both air and ground information. The air derived data is distance to go to touchdown obtained from a DME channel. The ground derived information is azimuth and elevation angle, which is linked to the aircraft via a Ku band radar. A ground controller can in turn monitor progress of the flight by observing the radar return on an azimuth and elevation scope. System coverage is shown in Figure F-23.

System Accuracy:

DME range: max (100 ft or 1% R) for airborne interrogator

GS: 0.03° 1σ

LOC: 0.01° encoding, total 0.03° 1σ

Antenna accuracy: 0.01° .

Two ground based, Ku band, antennas link azimuth and elevation information to the aircraft. The azimuth antenna and DME transponder are located on the centerline of the runway at the upwind end. A time delay keys the transponder to the vertical scanning antenna which is located 1,000 to 1,500 ft behind the intended touchdown point and offset from the runway centerline. Figure F-23 shows the information flow.

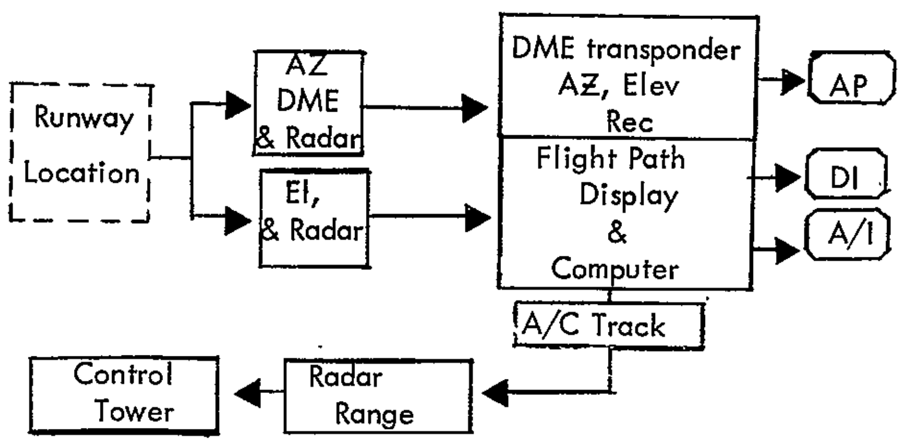


Figure F-23. AILS Information Flow

Although this system offers more accurate information, it can be saturated, the number of approach paths is limited, and the system can service a single runway, only the physical location of the airborne antenna is technically different and service in a downtown metropolitan area for VTOL may not be feasible.

F.8.1.3 Precision Approach Radar (PAR)

Table 2 lists the characteristics of Precision Approach Radar, an x-band system which presents azimuth and elevation information on the operator's display. The aircraft transponder can be used to assist in identification. Command steering and altitude signals are voice linked to the aircraft. Category II landings can be effected with the PAR. The signal flow diagram is shown in Figure F-24.

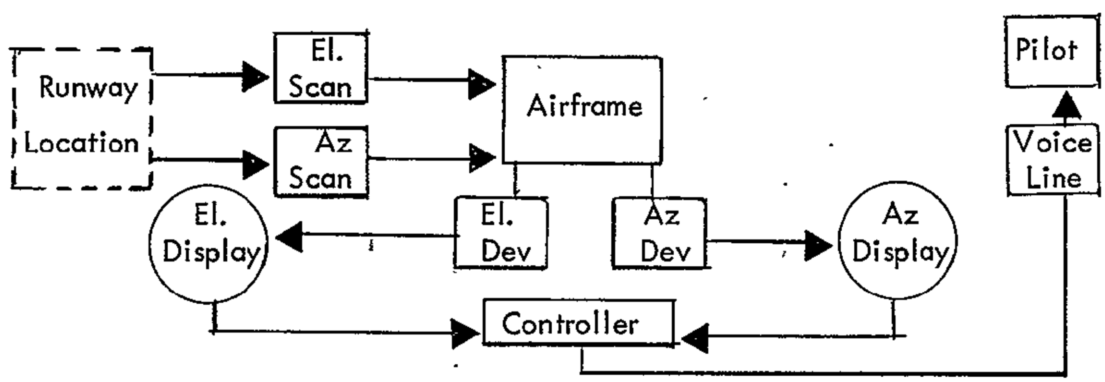


Figure F-24. PAR

The system is limited to control of one aircraft at a time, signal attenuation, loop delays and precision of pilot response to steering commands.

APPENDIX G

PILOT WORKLOAD ANALYSIS FOR NAVIGATION MANAGEMENT OF GA3 AND AIR CARRIER AIRCRAFT

Appendix G presents the results of an analysis of pilot workload related to navigation management tasks for GA - 3 and aircarrier aircraft operating in the proposed advanced navigation/ATC system.

Eight major tasks were identified for what is called the General (IFR controlled airspace) Mission and seven major tasks were listed for the Landing, Category II(b) Weather Minima, mode of operation. They can be related to the overall pilot management task by referring to the Event Sequence Diagrams of Appendix A. The specific functions include:

General Mission:

(1) Set up system - initial,
(2) Review current MET forecast,
(3) Reprogram system - inflight,
(4) Set surveillance link,
(5) Acquire steering data,
(6) Check flight plan status,
(7) Update Meteorological forecast, and
(8) Downlink ATC report.

Landing, Category IIb Minima:

(1) Update Meteorological forecast,
(2) Insert initial differential time difference,
(3) Check flight plan status,
(4) Prepare for Approach,
(5) Reprogram inflight system,
(6) Set surveillance link,
(7) Acquire steering data.

Ten navigation system configurations were subjected to evaluation. Table G-I relates system configuration to aircraft type and related mission.

TABLE G-I.
CANDIDATE SYSTEM USERS

System	Use	Class of User Aircraft				
		VTOL	VTOL-Helicopter	STOL	CTOL & GA3	SST
v1	Short Haul	x		x	x	
v2	Short Haul	x		x		
v3	Short Haul Terminal Area Altitudes	x	x	x		
v4	Long Haul				x	x
v5	Short Haul	x		x		
v6	Short Haul Terminal Area Altitudes	x	x	x		
v7	Long Haul				x	x
v8	Short/Long Haul	x	x	x	x	x
v9	Short Haul	x	x	x	x	
v10	Short Haul*	x	x	x		

*Air Taxi

In all cases the airborne system was assumed to be operating in accordance with an established Flight Plan Reference while in the General Mission mode. The ground-based ATC system was assumed to have the equivalent stored Flight Plan Reference. Wherever the equipment and related pilot tasks are identical in succeeding systems, the items are omitted and replaced with the comment "Repeat tasks of system v1". System differences are summarized in Table G-II. Note that workload analysis for the approach and landing phase was completed for only four of the systems.

Following the pages which list the tasks, operating times and utilization factors, is presented a brief description of the "straw-man" control-display used to evaluate pilot-subject workload. It represents a synthesis of control-display systems currently available from a number of manufacturers. The C-D unit contains a number of new I/O modes found to be necessary for operation of sub-systems of the postulated advanced navigation/ATC system. The operational procedures were specified in sufficient detail that a reasonable assessment of pilot workload could be completed.

A control display unit for a hypothetical moving map display, again only representative of currently available production systems, is described in the final paragraphs of this appendix.

TABLE G-II
SYSTEM ELEMENTS AND THEIR CANDIDATE SYSTEM UTILIZATION

System Elements "V"-	System Configurations in Which Used (v-series) 1	2	3	4	5	6	7	8	9	10
General Mission										
Low Frequency, Ground Based, Time Difference Receiver	x	x	x	x	-	-	-	-	-	x
*Air Data System	x	x	-	x	x	-	-	-	-	-
Area Navigation & Guidance Computer	x	x	x	x	x	x	x	-	x	x
Air Carrier Control/Display Interface Unit	x	x	x	x	x	x	x	-	-	-
VHF Digital Data Link (Primary Comm.)	x	x	x	x	x	x	x	x	x	x
VHF Voice Link (Secondary Comm.)	x	x	x	x	x	x	x	x	x	x
Moving Map Display		x	x	-	-	x	-	-	-	x
Doppler Radar (Ground Speed Only)			x	-	-	x	-	x	x	x
Inertial Navigation System (INS)				x	-	-	x	-	-	-
NAV SAT UHF Receiver and Processor					x	x	x	-	-	-
VOR NAV/Comm. Receiver								x	x	-
DMF Receiver								x	x	-
Course Line Computer								x	-	-
Landing, Cat IIb Minima										
Vertical Nav. Subroutine	x		x		x	x				
Precision DME	x		x		x	x				
Marker Beacon Receiver (MBR)	x				x	-				
Radar Altimeter	x		x		x	x				
FL Radar	x		x		x	x				
Inertial Navigator	x		-		x	-				
Doppler Radar System			x		-	x				
NAV SAT					x	x				
Differential Time Difference Reception					x	x				

Note: Omission of Air Data System refers to Velocity information only.

G.1 AIR CARRIER CONTROL DISPLAY UNIT

Figure G-1 shows the layout of the air carrier control display unit assumed for the workload evaluation. The panel was configured solely as a straw-man device for use in assessing the navigation management tasks of the postulated advanced navigation/traffic control system. It contains the modes, functions and data I/O capability required by the pilot for control of the candidate navigation systems.

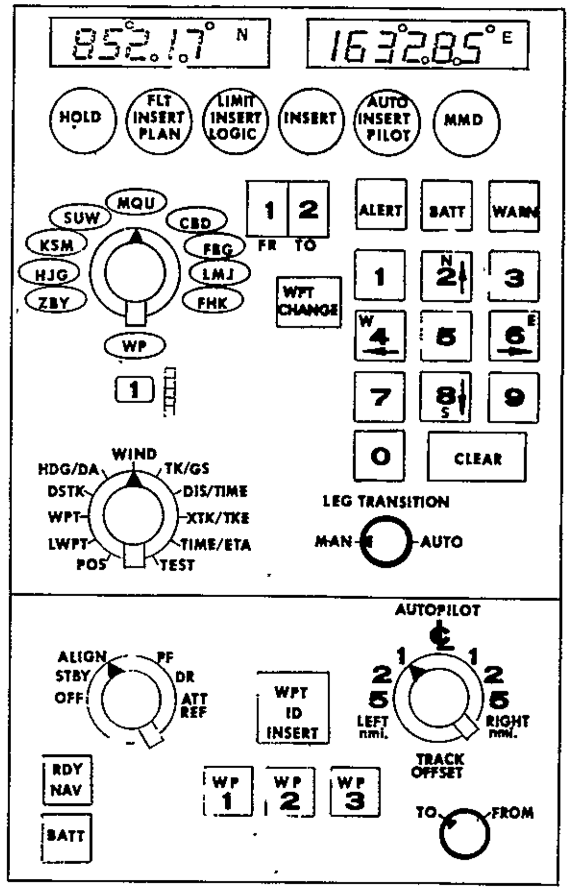


Figure G.1. Aircarrier Control/Display Unit

G.1.1 Modes of Operation

(1) Hold: a mode used in-flight for flight plan status check. Data output is frozen while internal computations continue. Selection of a function switch variable (WIND, TK/GS, DIS/TIME, etc.) reads out variables at the time "Hold" is depressed.

(2) Flight Plan Insert: a mode which permits magnetic tape, paper tape, or magnetic card read-in of flight plan. (Data link read-in is a desirable feature.)

(3) Limit Logic Insert: permits read-in of terminal area and enroute Limit Logic variables.

(4) Insert: keyboard or coded waypoint data is inserted by engaging this mode.

(5) Autopilot Insert: permits sequential insert of three autopilot waypoints.

(6) MMD: initiates moving map display operation.

(7) Leg Transition: Manual mode requires manual cycling of flight path legs; Auto mode engages automatic flight control system flight with automatic leg cycling.

(8) Navigation: PF mode uses NAV SAT (or VOR/DME or GBTD); DR uses air data (or doppler, or INS).

G.1.2 Function Operation

(1) Waypoint Insert: Set function switch on waypoint (WPT), set thumbwheel for waypoint identification (1, 2, 3 . . . 9); Option (1) - select coded waypoint (ZBY, HJG . . .), depress INSERT; Option (2) - select WP on coded waypoint, use keyboard insert, depress INSERT.

(2) Waypoint Change: Set thumbwheel for waypoint identification (1, 2, 3, . . . 9); Option (1) - select WP, insert keyboard data, depress INSERT; Option (2) - select coded waypoint, depress INSERT.

(3) Autopilot: Sets up three waypoints for track following with automatic flight control system; depress autopilot insert; Option (1) - select coded waypoint, depress WPT ID INSERT, depress WP 1; repeat through WP 2, WP 3; Option (2) - select waypoint code WP, set thumbwheel waypoint identification, depress WPT ID INSERT, depress WP 1; repeat for WP 2, WP 3; Option (3) - set waypoint code WP; enter keyboard waypoint, depress WP 1; repeat for WP 2, WP 3.

(4) Autopilot: Track offset engaged by depressing Autopilot Insert, selecting offset (1, 2, 5 nmi; right, left); TO used in normal

flight, FROM reverses waypoints (see Holding Pattern event sequence diagram, Appendix A).

(5) MMD: When engaged in the MMD mode, keyboard slews pens.

(6) Land Waypoint Insert: Set function switch to LWPT; waypoint read-in is the landing point sequence (LN1, LN2 . . .)

Table G-III following, lists the functions switch variables.

G.1.3 Control/Display Unit Operation

Pre-flight Phase

The operator turns the mode selector to STANDBY. When the device has warmed up, the operator turns the mode selector to ALIGN, and the function selector switch to WP. The waypoint selector switch is turned to 0, and the coordinates of the waypoint are stored in the system by pressing the number buttons and then the insert

TABLE G-III
AIRCARRIER CONTROL/DISPLAY UNIT - FUNCTION DESCRIPTIONS

Function Selection	Mode Selection	Right Display	Left Display
WIND	NAV	Reads wind speed in Kts.	Reads wind direction w.r.t. true north.
POSITION	NAV	Reads present Latitude of aircraft	Reads present Longitude of aircraft
DIS/TIME	NAV	Reads distance to go to waypoint	Reads time to go to waypoint
XTK/TKE	NAV	Reads X-Track Deviation	Reads difference w.r.t. true north of the actual track angle and the desired track angle of the aircraft
TK/GS	NAV	Reads track angle w.r.t. true north being made good	Reads ground speed
HDG/DA	NAV	Shows aircraft heading w.r.t. true north	Reads difference between track angle being made good and aircraft heading
DSTK STS	NAV	Desired track w.r.t. true north	INOPERATIVE
TIME/ETA	NAV	Reads time	Reads estimated time of arrival, next waypoint

button. The waypoint selector switch is then incremented by 1, and the process is repeated until all the necessary waypoints have been inserted. A maximum of nine waypoints is generally sufficient for the majority of short haul runs.

Departure, Arrival and Landing

If ATC requires the aircraft to fly to various waypoints, the operator will select the XTK/TKE function and then select the appropriate waypoints. If, however, ATC is giving the aircraft vectors for departure, the operator will select the HDG/DA function and comply with ATC commands.

Enroute

The operator will normally use the XTK/TKE function. The TO/FROM waypoint indicator identifies the leg and waypoint transition.

G.2 MOVING MAP DISPLAY/CONTROL UNIT

The air-taxi class of operator was assumed to have and to use a pictorial map display for area navigation. This affects the pilot workload assessment for this class of

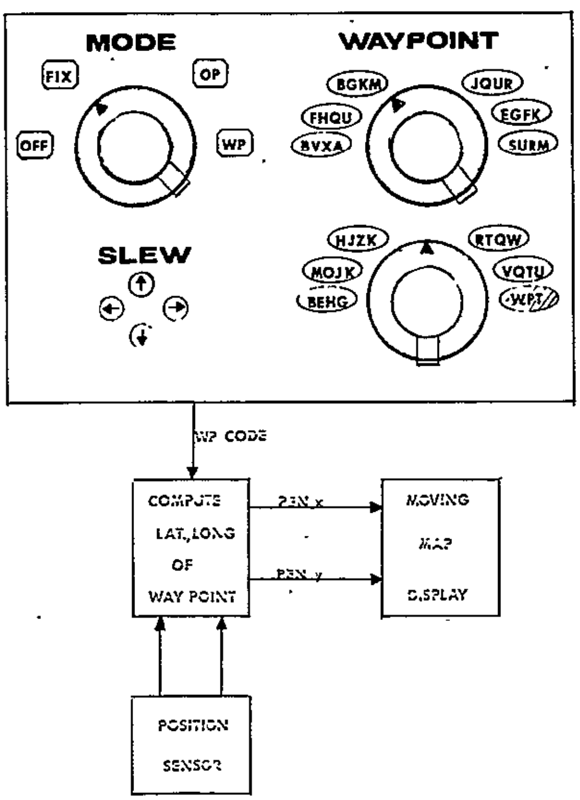


Figure G-2. Moving Map Display/Control Unit

TABLE G-IV
MOVING MAP DISPLAY - NAVIGATION MANAGEMENT EVENT

	Task	Time (sec)	Utilization Factor
Pre-Taxi and Taxi	Select FIX mode	2.1	8
	Select waypoint	8.6	8
	Slew pen	12.0	8
	Select OP mode	2.1	8
T/O and Enroute and Landing	Select waypoint	8.6	8
	Select nav. aid	8.6	8
Unprogrammed Waypoint	Select WP mode	2.1	8
	Slew pen	12.0	8
	Select GB waypoint	8.6	8
	Return to waypoint	8.6	8
	Ave	73.3	
	Pilot/Copilot		28.6%
	Navigator		40.0%

vehicle. A moving map display-control panel, illustrated in Figure G-2, was postulated for the evaluation. It provided for selectable coded waypoints and a map-to-computer read-in capability.

TABLE G-V
GENERAL MISSION, PILOT WORKLOAD ANALYSIS, System v1

SYSTEM v1, GENERAL MISSION

Assumptions
1. IFR Controlled Airspace,
2. Domestic Short Haul, Congested Airspace,
3. Flight Plan Reference

(1)

Airborne System v1
- LF GBTD Receiver
- Air Data System
- Area Navigation and Guidance Computer
- Air Carrier Control/Display Interface Unit
- VHF Digital Data Link (Primary)
- VHF Voice Link (Back up)

Ground System. Flight Plan Reference

Task 1
INITIAL SYSTEM SETUP

		Time	Utilization Factor
1.1	Switch on	1.1	7
1.2	Estimate map position	10	8
1.3	Select master/slave/chain	4 3	8
1.4	*Review flight plan and read waypoints ------		
1.5	*Insert present latitude estimate	14	8
1.6	Insert present longitude estimate	14	8
1.7	Select function switch – waypoint (WP)	2.1	8
1.8	Insert waypoint sequence identification number	2.1	8
1.9	Insert waypoint latitude	14	8
1.10	Insert waypoint longitude	14	8
1.11	Repeat waypoint insert through entire sequence ------		
1.12	Select function switch – land waypoint (LWP)	2.1	8
1.13	Insert land waypoint identification number	2.1	8
1.14	Insert land waypoint latitude	14	8
1.15	Insert land waypoint longitude	14	8
1.16	Insert land waypoint altitude	12	8
1.17	Repeat land waypoint insert through entire land sequence ------		
1.18	Initiate GBTD NAV search, acquisition, track	8.6	8
1.19	Select function switch – cross track distance, track angle error (XTE/TKE)	2 1	8

	Time	% Utilization Pilot
(1 WP, 1 LWP)	= 130.5 sec	= 28.6
(2 WP, 3 LWP)	= 244 8 sec	= 28 6
(4 WP, 3 LWP)	= 275 0 sec	= 28 6
(8 WP, 3 LWP)	= 425.4 sec	= 28.6

(LIMIT LOGIC GROWTH CAPABILITY)

		Time	Utilization Factor
1.20	Select function switch – Limit Logic (LL)	[2.1	8]*
1.21	Insert Terminal Area ΔETA	[6	8]
1.22	Insert Terminal Area Δ ground speed	[8	8]
1.23	Insert Terminal Area Δ cross track distance	[6	8]
1.24	Insert Terminal Area Δ altitude	[12	8]
1.25	Insert Enroute ΔETA	[6	8]
1.26	Insert Enroute Δ ground speed	[8	8]
1.27	Insert Enroute Δ cross track distance	[6	8]
1.28	Insert Enroute Δ altitude	[12	8]

Time = [66 1 sec] % Utilization Pilot = [28 6]

Task 2
REVIEW CURRENT METEOROLOGICAL (MET) FORECAST

		Time	Utilization Factor
2.1	Review current met forecast	30-300	8
2.2	Select function switch – WIND	2.1	8
2.3	Insert wind speed	8	8
2.4	Insert wind heading	8	8
2.5	Select function switch – (XTE/TKE)	2.1	8

Time = 50 sec % Utilization Pilot = 28.6

*All data insert includes reading data word
** [ ] parentheses indicate growth times only

Task 3a
SYSTEM REPROGRAM INFLIGHT (a)

		Time	Utilization Factor
3.1a	Select function switch – WPT	2.1	8
3.2a	Select vector waypoint identification number	8.6	8
3.3a	Insert vector waypoint latitude	14	8
3.4a	Insert vector waypoint longitude	14	8
3.5a	Repeat vector waypoint insert through entire sequence ------		
3.6a	Select function switch (XTE/TKE)	2.1	8

	Time	% Utilization Pilot
(1 WP)	= 40.8 sec	= 28.6
(2 WP)	= 77.4 sec	
(3 WP)	= 114.0 sec	

Task 3b
SYSTEM REPROGRAM INFLIGHT – (3) CODED WAYPOINTS (b)

		Time	Utilization Factor
3.1b	Select function switch – WPT	2.1	8
3.2b	Select vector waypoint identification number	8.6	8
3.3b	Select coded waypoint	2.1	8
3.4b	Insert waypoint	1.1	8
3.5b	Select vector waypoint identification number	2.1	8
3.6b	Select coded waypoint	2.1	8
3.7b	Insert waypoint	1.1	8
3.8b	Select vector waypoint identification number	2.1	8
3.9b	Select coded waypoint	2.1	8
3.10b	Insert waypoint	1.1	8
3.11b	Select function switch – (XTE/TKE)	2.1	8

Time = 26.6 sec %Utilization Pilot = 28.6

Task 4
SET SURVEILLANCE LINK

		Time	Utilization Factor
4.1	Set aircraft identity code in transponder	8.6	8
4.2	Set ATC code in transponder	8.6	8
4.3	Set system for interrogation	1.1	8
4.4	Set message format – (ABBR/STD)	2.1	8

Time = 20 4 sec % Utilization = 28 6

Task 5
ACQUIRE STEERING DATA

		Time	Utilization Factor
5.1	Monitor track angle error (TKE)	1.1	3
5.2	Steer revised course ------		

Time = 1.1 sec % Utilization Pilot = 10.7

Task 6
FLIGHT PLAN STATUS CHECK

If LIMIT LOGIC:

		Time	Utilization Factor
6.1	Select function switch – Limit Logic (LL)	2.1	8
6.2	Monitor tolerance – Δ alphanumeric	1.1	3

Time = 3.2 sec % Utilization Pilot = 22.4

If NO LIMIT LOGIC.

		Time	Utilization Factor
6.1	Heading check and reset	5	8
6.2	Depress computer function switch – HOLD	2.1	8
6.3	Monitor and read cross track distance (XTK)	2 2	3
6.4	Select function switch – TK/GS	2.1	8
6.5	Monitor and read ground speed	2.2	3
6.6	Select function switch – DIS/TIME	2.1	8
6.7	Monitor and read distance to go	2.2	3
6.8	Monitor and read time to go	2.2	3

*all 8 waypoints, 3 land points

Table G-IV contains a list of the operating procedures assumed for the evaluation. The task times and percentage of pilot utilization computed for the assumed device are shown below. (See Tables G-V through G-XIII.)

TABLE G-V
GENERAL MISSION, PILOT WORKLOAD ANALYSIS, System v1 (cont'd)

Task 6 (cont)		Time	Utilization Factor
6.9	Select function switch - TIME/ETA	2.1	8
6.10	Monitor and read time	2.2	3
6.11	Monitor and read ETA	2.2	3
6.12	Select function switch - XTK/TKE	2.1	8
6.13	Flight level check, monitor, and reset	6.7	8
6 14	Fuel check and record	10	8

Time = 45.4 sec % Utilization Pilot = 23.2

Task 7

UPDATE MET FORECAST

7.1	Update met forecast	60	17

Time = 60 sec % Utilization Pilot = 60.2

Task 8

DOWNLINK ATC REPORT

8.1	Release standard report	1.1	8

Time = 1.1 sec % Utilization Pilot = 28.6

*Total Time = 717 sec % Utilization Pilot = 30.9

Eliminate MET forecast update

Total Time = 657 sec % Utilization Pilot = 28.2

SYSTEM v1, APPROACH & LANDING

Assumptions 1. CAT IIb Landing
2 Flight Plan Reference

System v1 (Instrument Approach & Landing Subsystem

System v1
Area Navigation Computer with Vertical Channel
PDME
MBR
Radar Altimeter
FL Surveillance Radar
INS

(1)

Task 1		Time	Utilization Factor
UPDATE MET FORECAST			
1.1	Update met forecast	60	17
1.2	Select function wind	2.1	8
1.3	*Insert wind heading	8.	8
1.4	*Insert wind speed	8	8
1 5	Select function switch - (XTE/TKE)	2.1	8

Time = 80.2 sec %Utilization Pilot = 52.6

Task 2

INITIAL DIFFERENTIAL TIME DIFFERENCE INSERT

2.1	Select terminal area DTD VHF channel	10	8
2.2	Set DTD VHF channel	8.6	8
2.3	Monitor DTD magnitudes	15.8	1

*Monitor with operational INS

Task 3	Time	Utilization Factor
FLIGHT PLAN STATUS CHECK		

Repeat tasks of system v1

Time = 45.4 sec % Utilization Pilot = 23.2

Approaching final waypoint--

Task 4

PREPARATION FOR APPROACH

4.1	Monitor DTD magnitudes	15.8	1
4.2	Record DTD value ΔTD1, ΔTD2	10	8
4.3	Insert DTD value ΔTD1	9 8	8
4.4	Insert DTD value ΔTD2	9 8	8
4.5	Update command insert	1.1	8
4.6	Select function switch - DR update	2.1	8
4.7	Insert update command	1.1	8
4 8	Select function switch - (XTE/TKE)	2.1	8
4.9	Set mode switch - LAND	1.1	8
4.10	LAND waypoints enter store------------------------------		
4.11	Select DME channel	10	8
4.12	Set PDME channel	8 6	8
4.13	Set Marker Beacon Receiver channel	8 6	8
4.14	Select DME channel	10	8
4.15	Set PDME channel	8.6	8
4.16	Monitor MBR LWP1	2.1	3
4.17	Initiate radar altimeter update	2 1	8
4.18	Monitor MBR LWP2	2 1	3
4.19	Initiate radar altimeter update	2 1	8
4.20	Monitor MBR LWP3	2.1	3

Time = 90.6 sec % Utilization Pilot = 23 0

*Total Time = 481 7 sec % Utilization Pilot = 30 2

*Total terminal area navigation management

Task 4 (cont.)		Time	Utilization Factor
4.21	Record DTD values TD1, TD2	10	8
4.22	Insert DTD value, TD1	9.8	8
4.23	Insert DTD value, TD2	9.8	8
4 24	Update command insert	1.1	8

Time = 65.1 sec % Utilization Pilot = 22 5

Task 5

INFLIGHT SYSTEM REPROGRAM (TERMINAL AREA VECTOR WAYPOINTS)

5.1 Repeat tasks of system v1
(1 WP) Time = 40 8 sec % Utilization Pilot = 28.6
(2 WP) = 77.4 sec
(3 WP) = 114.0 sec

Task 6

INFLIGHT SYSTEM REPROGRAM (TERMINAL LANDING WAYPOINTS)

6.1 Repeat tasks of system v1
(4 WP) Time = 178 9 sec % Utilization Pilot = 28.6

Task 7

SURVEILLANCE LINK SET

7.1 Repeat tasks of system v1

Time = 20.4 sec % Utilization Pilot = 28 6

Task 8

STEERING DATA ACQUISITION

8.1	Monitor track angle error (TKE)	1 1	3
8 2	Steer revised course ------------------------------		

Time = 1.1 sec % Utilization Pilot = 10.7

TABLES G-VI and G-VII
GENERAL MISSION, PILOT WORKLOAD ANALYSIS, Systems v2 and v3

SYSTEM v2, GENERAL MISSION

Assumptions. 1. IFR Controlled Airspace,
2. Domestic Short Haul, Congested Airspace
3. Flight Plan Reference

(2)

System v2

LF GBTD Receiver
Air Data System
Area Navigation and Guidance Computer
Air Carrier Control/Display Interface Unit
Moving Map Display
VHF Digital Data Link (Primary)
VHF Voice Link (Back up)
(Receive DTD ATIS Signal)

Task 1		Time	Utilization Factor
INITIAL SYSTEM SETUP			
1 1	Switch on	1.1	7
1.2	Estimate map position	10 0	8
1.3	Select master/slave/chain	4 3	8
1 4	*Review flight plan and read waypoints		
1 5	Select function switch - waypoint (WP)	2.1	8
1.6	Insert waypoint sequence identification number	2.1	8
1 7	Insert waypoint latitude	14 0	8
1 8	Insert waypoint longitude	14 0	8
1.9	Repeat waypoint insert through entire sequence		
1.10	Select function switch - land waypoint (LWP)	2.1	8
1.11	Insert land waypoint identification number	2.1	8
1 12	Insert land waypoint latitude	14.0	8
1.13	Insert land waypoint longitude	14 0	8

*All data insert includes reading data word

Task 2		Time	Utilization Factor
2 1	Insert land waypoint altitude	12	8
2 2	Repeat land waypoint insert through entire land sequence		
2 3	Select function switch - position fix (POS)	2.1	8
2 4	Select mode switch - moving map display (MMD)	2.1	8
2 5	Slew MMD pen to aircraft estimated latitude longitude	12	8
2 6	Depress insert	1.1	8
2.7	Select mode switch - automatic (auto)	2.1	8
2 8	Initiate GBTD NAV search, acquisition, track	8 6	8
2 9	Select function switch - cross track distance, track angle error (XTE/TKE)	2.1	8

(1 WP, 1 LWP)	Time = 120.5 sec	% Utilization Pilot = 28 6
(2 WP, 4 LWP)	= 234.8 sec	= 28.6
(4 WP, 4 LWP)	= 265 0 sec	= 28.6
(8 WP, 4 LWP)	= 415.4 sec	= 28 6

MMD saves 10 sec on initial set up.

(LIMIT LOGIC GROWTH CAPABILITY)

Repeat tasks of system v1

Time = [66 1 sec] % Utilization Pilot = [28.6]**

Task 3
REVIEW CURRENT MET FORECAST

3.1 Repeat tasks of system v1

Time = 50 sec % Utilization Pilot = 28 6

**Indicates growth item only

Task 4		Time	Utilization Factor
INFLIGHT SYSTEM REPROGRAM			
4 1	Select function switch - WPT	2.1	8
4 2	Select mode switch - MMD	2.1	8
4 3	Select waypoint identification number	8.6	8
4 4	Slew MMD pen to vector waypoint	12	8
4.5	Depress insert	1.1	8
4.6	Repeat vector waypoint insert through entire sequence		
4 7	Select mode switch - automatic (auto)	2.1	8
4 8	Select function switch - (XTE/TKE)	2.1	8

(1 WP)	Time = 30.1 sec	% Utilization Pilot = 28.6
(2 WP)	= 45.3 sec	
(3 WP)	= 60.5 sec	

Task 5
SURVEILLANCE LINK SET

5 1 Repeat tasks of system V1

Time = 20 4 sec % Utilization Pilot = 28 6

Task 6
STEERING DATA ACQUISITION

6 1 Monitor track angle error (TKE) 1.1 3
6 2 Steer revised course

Time = 1 1 sec % Utilization Pilot = 10 7

Task 7
FLIGHT PLAN STATUS CHECK

7.1 Repeat tasks of system V1

Time = 45 4 sec % Utilization Pilot = 23.2

Task 8		Time	Utilization Factor
UPDATE MET FORECAST			
8 1	Update met forecast	60	17

Time = 60 sec % Utilization Pilot = 60 2

Task 9
DOWNLINK ATC REPORT

9.1 Release standard report 1.1 8

Time = 1.1 sec % Utilization Pilot = 30.9

Total Time = 654 sec % Utilization Pilot = 31 1

Eliminate MET forecast update

Total time = 594 sec % Utilization Pilot = 28.9

SYSTEM v3, GENERAL MISSION

Assumptions 1. IFR Controlled Airspace,
2. Short Haul Congested Airspace - Terminal Area Altitudes,
3 Flight Plan Reference

(3)

SYSTEM v3

LF GBTD
Doppler Radar System
Area Navigation and Guidance Computer
Air Carrier Control/Display Interface Unit
VHF Digital Data Link (Primary)
VHF Voice Link (Back up)
Moving Map Display

Task	Time	Utilization Factor

See System V2 for task sequence, task times and % utilization pilot.

TABLES G-VII and G-VIII
GENERAL MISSION, PILOT WORKLOAD ANALYSIS, Systems v3 and v4

SYSTEM v3, APPROACH AND LANDING

Assumptions: 1 IFR Controlled Airspace
2. CAT IIb LANDING
3. Flight Plan Reference

③

System v3 (Land)

Area Navigation Computer with Vertical Channel
PDME
Radar Altimeter
FL Surveillance Radar
Doppler Radar System

Task 1		Time	Utilization Factor
UPDATE MET FORECAST			
1.1	Update met forecast	60	17
1.2	Select function wind	2.1	8
1.3	*Insert wind heading	8	8
1.4	*Insert wind speed	8	8
1.5	Select function switch - (XTE/TKE)	2.1	8

Time = 80.2 sec   % Utilization Pilot = 52.6

Task 2			
INITIAL DIFFERENTIAL TIME DIFFERENCE INSERT			
2.1	Select terminal area DTD VHF channel	10	8
2.2	Set DTD VHF channel	8.6	8
2.3	Monitor DTD magnitudes	15.8	1
2.4	Record DTD values ΔTD1, ΔTD2	10	8
2 5	Insert DTD value, ΔTD1	9.8	8
2.6	Insert DTD value, ΔTD2	9.8	8
2.7	Update command insert	1.1	8

Time = 65 1 sec   % Utilization Pilot = 22 5

Task 3
INFLIGHT SYSTEM REPROGRAM (TERMINAL AREA VECTOR WAYPOINTS)

3 1 Repeat tasks of system v1

(1 WP) Time = 40.8 sec   % Utilization Pilot = 28 6
(2 WP) = 77 4 sec
(3 WP) = 114 0 sec

Task 4
INFLIGHT SYSTEM REPROGRAM (TERMINAL LANDING WAYPOINTS)

4.1 Repeat tasks of system V1
(4 WP) Time = 178 9 sec   % Utilization Pilot = 28 6

Task 5
SURVEILLANCE LINK SET

5 1 Repeat tasks of system V1
Time = 20.4 sec   % Utilization Pilot = 28 6

Task 6
STEERING DATA ACQUISTION

		Time	Utilization Factor
6.1	Monitor track angle error (TKE)	1.1	3
	Steer revised course------------------------		

Time = 1 1 sec   % Utilization Pilot = 10 7

Task 7		Time	Utilization Factor
FLIGHT PLAN STATUS CHECK *			
7.1	Repeat tasks of system v1		

Time = 45.4 sec   % Utilization Pilot = 23 2

Approaching final waypoint------------------------

*Monitor with operational doppler system

Task 8			
PREPARATION FOR APPROACH			
8.1	Monitor DTD magnitudes	15.8	1
8.2	Record DTD value ΔTD1, ΔTD2	10	8
8.3	Insert DTD value ΔTD1	9 8	8
8.4	Insert DTD value ΔTD2	9 8	8
8.5	Update command insert	1.1	8
8.6	Select function switch - DR update	2.1	8
8.7	Insert update command	1.1	8
8.8	Select function switch - (XTE/TKE)	2 1	8
8.9	Set mode switch - LAND	1 1	8
8.10	LAND waypoints enter store------------------------		
8.11	Select DME channel	10	8
8.12	Set PDME channel	8 6	8

Time = 71.5 sec   % Utilization Pilot = 23 0

*Total Time = 463 sec   % Utilization Pilot = 30.0

*Total terminal area navigation management

SYSTEM v4, GENERAL MISSION

Assumptions 1. IFR Controlled Airspace,
2. Domestic/Oceanic Long Haul,
3. Flight Plan Reference

④

System v4

LF GBTD Receiver
Air Data System
INS
Area Navigation and Guidance Computer
Air Carrier Control/Display Interface Unit
VHF Digital Data Link (Primary)
VHF Voice Link (Back up)

Task 1		Time	Utilization Factor
INITIAL SYSTEM SETUP			
1.1	Switch on	1.1	7
1.2	Estimate map position	10	8
1 3	Select master/slave/chain	4 3	8
1.4	*Review flight plan and read waypoints ------------------------		
1.5	*Insert present latitude estimate	14	8
1 6	Insert present longitude estimate	14	8
1.7	Select function switch - waypoint (WP)	2 1	8
1.8	Insert waypoint sequence identification number	2 1	8
1.9	Insert waypoint latitude	14	8
1.10	Insert waypoint longitude	14	8
1.11	Repeat waypoint insert through entire sequence ------------------------		
1.12	Select function switch - land waypoint (LWP)	2 1	8
1.13	Insert land waypoint identification number	2 1	8
1.14	Insert land waypoint latitude	14	8
1.15	Insert land waypoint longitude	14	8
1.16	Insert land waypoint altitude	12	8
1.17	Repeat land waypoint insert through entire land sequence ------------------------		
1.18	Initiate GBTD NAV search, acquisition, track	8 6	8

*All data insert includes reading data word

TABLE G-IX
GANERAL MISSION, PILOT WORKLOAD ANALYSIS, System v5

1.1° Select mode switch – auto	2.1	8
1.20 Select NAV mode switch – align	2.1	8
1.21 Select mode switch – NAV	2.1	8
1.22 Select function switch – cross track distance, track angle error (XTE/TKE)	2.1	8

(1 WP, 1 LWP) Time = 136.5 sec % Utilization Pilot = 28.6
(2 WP, 3 LWP) = 250.8 sec = 28.6
(4 WP, 3 LWP) = 281 0 sec = 28.6
(8 WP, 3 LWP) = 431.4 sec = 28.6

(LIMIT LOGIC GROWTH CAPABILITY)

1.23 Select function switch – Limit Logic (LL)	[2.1	8]**
1.24 Insert Terminal Area ΔETA	[6	8]
1.25 Insert Terminal Area Δ ground speed	[8	8]
1.26 Insert Terminal Area Δ cross track distance	[6	8]
1.27 Insert Terminal Area Δ altitude	[12	8]
1.28 Insert Enroute ΔETA	[6	8]
1.29 Insert Enroute Δ ground speed	[8	8]
1.30 Insert Enroute Δ cross track distance	[6	8]
1.31 Insert Enroute Δ altitude	[12	8]

Time = [66 1 sec] % Utilization Pilot = [28.6]

** [ ] parenthesis indicates growth times only

Task 2	Time	Utilization Factor
REVIEW CURRENT MET FORECAST		
2.1 Review current met forecast	30-300	8
2.2 Select function switch – WIND	2.1	8
2.3 Monitor wind speed	8	8
2.4 Monitor wind heading	8	8
2.5 Select function switch – (XTE/TKE)	2.1	8

Time = 50 sec % Utilization Pilot = 28 6

Task 3		
INFLIGHT SYSTEM REPROGRAM		
3 1 Select function switch – WPT	2 1	8
3.2 Select vector waypoint identification number	8.6	8
3.3 Insert vector waypoint latitude	14	8
3 4 Insert vector waypoint longitude	14	8
3.5 Repeat vector waypoint insert through entire sequence	----------	----------
3 6 Select function switch – (XTE/TKE)	2 1	8

(1 WP) Time = 40 8 sec % Utilization Pilot = 28 6
(2 WP) = 77 4 sec
(3 WP) = 114 0 sec

Task 4		
SURVEILLANCE LINK SET		
4.1 Set aircraft identity code in transponder	8 6	8
4 2 Set ATC code in transponder	8 6	8
4.3 Set system for interrogation	1.1	8
4 4 Set message format – [ABBR/STD]	2 1	8

Time = 20 4 sec % Utilization Pilot = 28.6

Task 5	Time	Utilization Factor
STEERING DATA ACQUISITION		
5 1 Monitor track angle error (TKE)	1.1	3
5.2 Steer revised course----------	----------	----------

Time = 1.1 sec % Utilization Pilot = 10.7

Task 6		
FLIGHT PLAN STATUS CHECK		
IF LIMIT LOGIC		
6.1 Select function switch – Limit Logic (66)	2.1	8
6.2 Monitor tolerance – Δ alphanumeric	1.1	3

Time = 3.2 sec % Utilization Pilot = 22.4

IF NO LIMIT LOGIC		
6.1 Heading check and reset	5	8
6.2 Depress computer function switch – HOLD	2.1	8
6.3 Monitor and read cross track distance (XTK)	2.2	3
6.4 Select function switch – TK/GS	2.1	8
6.5 Monitor and read ground speed	2.2	3
6.6 Select function switch – DIS/TIME	2.1	8
6.7 Monitor and read distance to go	2 2	3
6.8 Monitor and read time to go	2.2	3
6.9 Select function switch – TIME/ETA	2.1	8
6.10 Monitor and read time	2.2	3
6.11 Monitor and read ETA	2.2	3
6.12 Select function switch – XTK/TKE	2.1	8
6.13 Flight level check, monitor, and reset	6.7	8
6.14 Fuel check and record	10	8

Time = 45.4 sec % Utilization Pilot = 23.2

Task 7	Time	Utilization Factor
UPDATE MET FORECAST		
7.1 Update met forecast	60	17

Time = 60 sec % Utilization Pilot = 60 2

Task 8		
DOWNLINK ATC REPORT		
8.1 Release standard report	1 1	8

Time = 1.1 sec % Utilization Pilot = 28 6

*Total Time = 723 sec % Utilization Pilot = 30 9

Eliminate MET forecast update

Total Time = 663 sec % Utilization Pilot = 28 2

*all 8 waypoints, 3 land points

SYSTEM v5, GENERAL MISSION

Assumptions
1 VTOL Aircraft,
2. IFR Controlled Airspace,
3 Flight Plan Reference

System v5

(5)

NAV SAT UHF Receiver and Preprocessor
Air Data System
Area Navigation and Guidance Computer
Air Carrier Control/Display Interface Unit
VHF Digital Data Link (Primary)
VHF Voice Link (Back up)

TABLES: G-IX, G-X, G-XI
GENERAL MISSION. PILOT WORKLOAD ANALYSIS, Systems v5, v6 and v7

SYSTEM v5, APPROACH & LAND

(5)

System v5 (Land)

System v5
NAV SAT UHF Receiver and Preprocessor
Area Navigation Computer with Vertical Channel
INS
PDME
DTD Reception
Radar Altimeter
MBR
FL Surveillance Radar

VTOL System v5 (Land)

Operates as System V1 landing. Change only to NAV SAT selection in terms

SYSTEM v6, GENERAL MISSION

Assumptions: 1 IFR Controlled Airspace,
2. Short Haul Congested Airspace,
3. Terminal Area Altitudes,
4 Flight Plan Reference

(6)

System v6

NAV SAT UHF Receiver and Preprocessor
Area Navigation and Guidance Computer
Air Carrier Control Display Interface Unit
Doppler Radar System
Moving Map Display
VHF Digital Data Link (Primary)
VHF Voice Link (Back up)

Operates as System v3

SYSTEM v6, APPROACH & LANDING

Assumptions 1. Cat IIb Landing Minima,
2 Flight Plan Reference,
3 VTOL System

(6)

System v6 (Land)

NAV SAT UHF Receiver and Preprocessor
Area Navigation and Guidance Computer with Vertical Channel
Doppler Radar System
PDME
DTD Reception
Radar Altimeter
FL Surveillance Radar

Operates as System v3 landing

SYSTEM v7, GENERAL MISSION

Assumptions. 1. IFR Controlled Airspace
2. VTOL System
3. Flight Plan Reference

(7)

System v7

NAV SAT UHF Receiver and Preprocessor
INS
Area Navigation and Guidance Computer
Air Carrier Control/Display Interface Unit
VHF Digital Data Link (Primary)
VHF Voice Link (Back up)

Operates as System V4.

SYSTEM v8, GENERAL MISSION

Assumptions. 1. IFR Controlled Airspace,
2. Domestic Short Haul and Long Haul Congested Airspace,
3. Flight Plan Reference

(8)

System v8

VOR NAV/Comm Receiver
UHF DME
Course Line Computer
Doppler Radar System
VHF Digital Data Link (Primary
VHF Voice Link (Back up)

Task 1		Time	Utilization Factor
INITIAL SYSTEM SETUP			
1.1	Switch on	1.1	8
1 2	Select VOR channel	15	8
1.3	Set VOR channel	8.6	8
1.4	Select DME channel	1.5	8
1.5	Set DME channel	8.6	8

Time = 48.3 sec % Utilization Pilot = 28 6

Task 2			
REVIEW CURRENT MET FORECAST			
2.1	Review current met forecast	30	8
2.2	Monitor wind speed	8	8
2.3	Monitor wind heading	8 -	8

Time = 46 sec % Utilization Pilot = 28 6

Task 2 (cont.)		Time	Utilization Factor
INFLIGHT SYSTEM REPROGRAM (OR MANDATORY PROGRAM)			
2.4	Select VOR channel	15	8
2.5	Set VOR channel	8 6	8
2.6	Select DME channel	15	8
2.7	Set DME channel	8.6	8
2 8	Select offset radial	10	8
2.9	Insert offset radial	8.6	8
2.10	Select offset distance	10	8
2.11	Insert offset distance	8.6	8
2.12	Identify station(s)	5	1
2.13	Set station ident in data link	8.6	8

Time = 98 sec % Utilization Pilot = 28.6
*Time = 78 sec % Utilization Pilot = 28.6

TABLE G-XII
GENERAL MISSION, PILOT WORKLOAD ANALYSIS, System v9

Task 3
SURVEILLANCE LINK SET

		Time	Utilization Factor
3.1	Set circraft identity code in transponder	8.6	8
3.2	Set ATC code in transponder	8 6 *	8
3.3	Set station ident in data link	8 6	8
3.4	Set system for interrogation	1 1	8
3.5	Set message format - (ABBR/STD)	2 1	8

Time = 29 0 sec % Utilization Pilot = 28 6

*assumes offset radial and distance pre-determined

Task 4		Time	Utilization Factor
	STEERING DATA ACQUISITION		
4.1	Set desired magnetic course	4.3	8
4 2	Monitor track angle error (TKE) on HSI	1 1	3
4.3	Steer revised course	----------	----------

Time = 5.4 sec % Utilization Pilot = 24.9

Task 5
FLIGHT PLAN STATUS CHECK

		Time	Utilization Factor
5.1	Heading check and reset	5-60	8
5.2	Read DTG	1 1	3
5.3	Record DTG	3	8
5.4	Read magnetic bearing to waypoint	1.1	3
5.5	Record magnetic bearing to waypoint	3	8
5.6	Plot position on map	20	8
5.7	Read cross track distance	10	8
5.8	Read and record elapsed time	6 2	8
5.9	Read and record ground speed	6.2	8
5.10	ETA check and record	10	8
5.11	ETE check and record	10	8
5.12	Flight level check, monitor, and reset	6 7	8
5.13	Fuel check and record	10	8

Time = 89.3 sec % Utilization Pilot = 28.6

Task 6
UPDATE MET FORECAST

		Time	Utilization Factor
6.1	Update met forecast	60	17

Time = 60 sec % Utilization Pilot = 60.7

Task 7		Time	Utilization Factor
	DOWNLINK ATC REPORT		
7.1	Release standard report	1.1	8

Time = 1.1 sec % Utilization Pilot = 28.6

*Total Time = 377 1 sec % Utilization Pilot = 33 6

Eliminate MET forecast update

Total Time = 317 sec % Utilization Pilot = 28 5

Landing performed as in system v3.

Requires ground system convert surveillance information.

Task 8
LANDING SYSTEM PROGRAM

		Time	Utilization Factor
8 1	Select VOR channel	5	8
8.2	Set VOR channel	8.6	8
8.3	Select DME channel	5	8
8.4	Set DME channel	8 6	8
8 5	Select offset radial	10	8
8.6	Insert offset radial	8 6	8
8 7	Select offset distance	10	8
8.8	Insert offset distance	8.6	8
8.9	Select offset radial	10	8
8.10	Insert offset radial	8.6	8
8.11	Select offset distance	10	8
8.12	Insert offset distance	8 6	8
8.13	Select offset radial	10	8

*Only one waypoint set

Task 8 (cont.)		Time	Utilization Factor
8.14	Insert offset radial	8 6	8
8.15	Select offset distance	10	8
8.16	Insert offset distance	8.6	8

Time = 138 sec % Utilization Pilot = 28.6

SYSTEM v9, GENERAL MISSION

Assumptions 1. IFR Controlled Airspace,
2. Domestic Short Haul/Congested Airspace,
3 Flight Plan Reference

System v9
(9)
VOR NAV/Comm Receiver
UHF DME
Area Navigation and Guidance Computer
Doppler Radar System
VHF Digital Data Link (Primary)
VHF Voice Link (Back up)

Task 1		Time	Utilization Factor
	INITIAL SYSTEM SETUP		
1.1	Switch on	1.1	7
1.2	*Review flight plan and read waypoints	----------	----------
1.3	Insert present latitude estimate	14	8
1.4	Insert present longitude estimate	14	8
1.5	Select function switch - VORTAC WP	2.1	8
1 6	Insert waypoint sequence identification number	2.1	8
1.7	Insert VORTAC latitude	14	8
1.8	Insert VORTAC longitude	14	8
1.9	Insert offset radial	12	8
1.10	Insert offset distance	12	8
1.11	Repeat waypoint insert through entire sequence	----------	----------
1.12	Select function switch - land VORTAC WP (LVWP)	2.1	8
1.13	Insert land waypoint sequence identification number	2.1	8
1.14	Insert VORTAC(T) latitude	14	8
1.15	Insert VORTAC(T) longitude	14	8
1.16	Insert land offset radial	12	8
1.17	Insert land offset distance	12	8
1.18	Insert land offset altitude	12	8
1.19	Repeat land waypoint sequence identification number	----------	----------
1.20	Select function switch - cross track distance, track angle error (XTE, TKE)	2.1	8
1.21	Select VOR frequency	15	8
1.22	Set VOR frequency	8.6	8
1.23	Select DME frequency	15	8
1.24	Set DME frequency	8 6	8

*All data insert includes reading data word

TABLE G-VIII
GENERAL MISSION, PILOT WORKLOAD ANALYSIS, System v10

(1 WP, 1 LWP) Time = 202.8 sec % Utilization Pilot = 28.6
(2 WP, 3 LWP) = 388.8 sec
(4 WP, 3 LWP) = 496 8 sec
(8 WP, 3 LWP) = 712 8 sec

Task 2

REVIEW CURRENT MET FORECAST

2.1	Review current met forecast	30	8
2.2	Monitor wind speed	8	8
2.3	Monitor wind heading	8	8

Time = 46 sec % Utilization Pilot = 28.6

Task 3		Time	Utilization Factor
INFLIGHT SYSTEM CHANGE			
3.1	Select VOR frequency	15	8
3.2	Set VOR frequency	8 6	8
3.3	Select DME frequency	10	8
3.4	Set DME frequency	8.6	8

Time = 42 2 sec % Utilization Pilot = 28 6

Task 4

INFLIGHT SYSTEM REPROGRAM

4.1	Select function switch - VORTAC WP	2.1	8
4.2	Select vector waypoint identification number	8 6	8
4.3	Select VORTAC latitude	10	8
4 4	Insert VORTAC latitude	14	8
4.5	Read VORTAC longitude	1.1	8
4 6	Insert VORTAC longitude	14	8
4 7	Select offset radial	10	8
4 8	Insert offset radial	12	8
4.9	Select offset distance	10	8
4 10	Insert offset distance	12	8
4.11	Repeat vector waypoint insert through entire sequence	----------	----------
4.12	Select function switch - (XTE/TKE)	2.1	8
4.13	Set VOR channel	8 6	8
4 14	Set DME channel	8 6	8
4.15	Identify station(s)	5	1

(1 WP) Time = 118.1 sec % Utilization Pilot = 28.6
(2 WP) = 203 3 sec
(3 WP) = 288.5 sec

Task 5

SURVEILLANCE LINK SET

5.1	Set aircraft identity code in transponder	8.6	8
5 2	Set ATC code in transponder	8.6	8
5.3	Set system for interrogation	1.1	8
5 4	Set message format - (ABBR/STD)	2.1	8

Time = 20.4 sec % Utilization Pilot = 28.6

Task 6

STEERING DATA ACQUISITION

6.1	Monitor track angle error (TKE)	1.1	3
6.2	Steer revised course	----------	----------

Time = 1.1 sec % Utilization Pilot = 10.7

Task 7

FLIGHT PLAN STATUS CHECK

IF LIMIT LOGIC:

7.1	Select function switch - Limit Logic (LL)	2.1	8
7.2	Monitor tolerance - alphanumeric	1.1	3

Time = 3.2 sec % Utilization Pilot = 22.4

IF NO LIMIT LOGIC

7.1	Heading check and reset	5	8
7.2	Depress computer function switch - HOLD	2.1	8
7.3	Monitor and read cross track distance (XTK)	2.2	3
7.4	Select function switch - TK/GS	2.1	8
7.5	Monitor and read ground speed	2.2	3
7.6	Select function switch - DIS/TIME	2.1	8
7.7	Monitor and read distance to go	2.2	3
7.8	Monitor and read time to go	2.2	3
7.9	Select function switch - TIME/ETA	2.1	8
7.10	Monitor and read time	2.2	3
7.11	Monitor and read ETA	2.2	3
7.12	Select function switch - XTK/TKE	2.1	8
7.13	Flight level check, monitor, and reset	6.7	8
7.14	Fuel check and record	10	8

Time = 45.4 sec % Utilization Pilot = 23.2

Task 8

UPDATE MET FORECAST

8.1	Update met forecast	60	17

Time = 60 sec % Utilization Pilot = 60.2

Task 9

DOWNLINK ATC REPORT

8.2	Release standard report	1.1	8

Time = 1.1 sec % Utilization Pilot = 28.6

Total Time = 1264 sec % Utilization Pilot = 29.9

Eliminate MET forecast update

Total Time = 1204 sec % Utilization Pilot = 28.4

SYSTEM v10, GENERAL MISSION

Assumptions
1. IFR Controlled Airspace
2. Domestic Short Haul, Congested Airspace, Air Taxi,
3. Flight Plan Reference

18

System v10
LF GBTD Receiver
Area Navigation and Guidance Computer (Minimum Automation)
Moving Map Display Interface Unit
Doppler Radar
VHF Digital Data Link (Primary)
VHF Voice Link (Back up)

Task 1		Time	Utilization Factor
INITIAL SYSTEM SETUP			
1.1	Switch on	1.1	7
1.2	Estimate map position	10	8
1.3	Select master/slave/chain	4.3	8
1.4	*Review flight plan and read waypoints	----------	----------
1.5	Select function switch - position fix (POS)	2.1	8
1.6	Select mode switch - moving map display (MMD)	2.1	8
1.7	Slew MMD pen to aircraft estimated latitude, longitude	12	8
1.8	Select function switch - WPT	2.1	8
1.9	Select initial waypoint	10	8

*All data insert includes reading data word

TABLE G-XIII
GENERAL MISSION, PILOT WORKLOAD ANALYSIS, System v10 (cont'd)

Task 1 (cont.)	Time	Utilization Factor
1.10 Locate initial waypoint	10	8
1.11 Select mode switch - MMD	2.1	8
1.12 Slew MMD pen to initial waypoint	12	8
1.13 Depress Insert	1.1	8
1.14 Select mode switch - AUTO	2.1	8
1.15 Select mode switch - MMD	2.1	8
Time = 73 1 sec	% Utilization Pilot = 28.6	

Task 2
REVIEW CURRENT MET FORECAST

2.1 Repeat tasks of system v2

Time = 50 sec % Utilization Pilot = 28 6

Task 3 INFLIGHT SYSTEM PROGRAM (Also for LANDING PROGRAM)		
3.1 Select waypoint	10	8
3.2 Locate waypoint	10	3
3.3 Select function switch - WPT	2.1	8
3.4 Select mode switch - MMD	2.1	8
3 5 Slew MMD pen to waypoint	12	8
3.6 Depress Insert	1 1	8
3.7 Select mode switch - AUTO	2.1	8
3.8 Select mode switch - MMD	2.1	8
Time = 41.5 sec	% Utilization Pilot = 23.0	

Repeat throughout mission---

Task 4
SURVEILLANCE LINK SET

4.1 Repeat tasks of system v1

Time = 20 4 sec % Utilization Pilot = 28 6

Task 5 STEERING DATA ACQUISITION	Time	Utilization Factor
5.1 Set desired magnetic course	4.3	8
5.2 Monitor track angle error (TKE) on HSI	1.1	3
5.3 Steer revised course-----------------------------------		
Time = 5.4 sec	% Utilization Pilot = 24.9	

Task 6 FLIGHT PLAN STATUS CHECK		
6.1 Heading check and reset	5-60	8
6.2 Read DTG	1.1	3
6.3 Record DTG	3	8
6.4 Read magnetic bearing to waypoint	1.1	3
6.5 Record magnetic bearing to waypoint	3	8
6.6 Plot position on map	20	8
6.7 Read cross track distance	10	8
6.8 Read and record elapsed time	6 2	8
6.9 Read and record ground speed	6 2	8
6.10 ETA check and record	10	8
6.11 ETE check and record	10	8
6.12 Flight level check, monitor, and reset	6.7	8
6.13 Fuel check and record	10	8
Time = 89.3 sec	% Utilization Pilot = 28 6	

Task 7 UPDATE MET FORECAST		
7.1 Update met forecast	60	17
Time = 60 sec	% Utilization Pilot = 60.7	

Task 8 DOWNLINK ATC REPORT	Time	Utilization Factor
8.1 Release standard report	1.1	8
Time = 1.1 sec	% Utilization Pilot = 28.6	

*Total Time = 711 sec % Utilization Pilot = 31 3

Eliminate MET forecast update

Total Time = 651 sec % Utilization Pilot = 29 4

*Only one waypoint set

APPENDIX H

NAVIGATION MANAGEMENT WORKLOAD ANALYSIS, GA1 AND GA2

This Appendix summarizes the results of one of the workload assessments performed in the study. In this instance, the subjects were pilots of GA1 and GA2 aircraft. Measurements were made of the typical operations and procedures which might be required of a pilot in the utilization of a number of feasible candidate navigation systems. In fact, 14 configurations were examined.

In addition to the workload summary, this Appendix summarizes the results of two brief analyses which were performed to establish the credibility of considering two general aviation systems. Both of these are GA aircraft navigation systems which utilize either NAV SAT or GBTD airborne receivers in conjunction with an automated ground system. The NAVSAT system is subject to saturation (See Appendix F, Section F.3.4) if either the fixing frequency of the general aviation user increases or if continuou surveillance information must be available to ATC. Therefore, to supplement the fixing frequency an air data along-track cross-track computer system was sized for general aviation application. Although the estimates of computer storage and speed are based on present day airborne general purpose computers, it was assumed this technology would be available in the 1980 time period for special purpose general aviation application. Therefore, the study was performed to compute, based on current state of the art, the solution time or the iteration rate that could be expected in the solution of along-track cross-track equations. If the solution rate is less than the update frequency requirement of the general aviation aircraft, or if the information is continually output, compatible to ATC surveillance interrogation rates, the system is a viable candidate for general aviation application. Section H.3 sizes the computation requirements.

In addition to the NAV SAT saturation problem, other advanced general aviation system problems must be resolved. GBTD and NAV SAT airborne receiver are configured in Systems g1, g2, g3, g4, g5, g6, g7 and g8 as repeaters. The airborne system receives time difference data, and repeats the received signals, for transmission to the ground system. The ground system computes the general aviation pilot guidance information and uplinks the signal to the aircraft for display. This configuration is extremely low cost and worthy of application. However, the GBTD CW systems present lane resolution ambiguities. A technique is outlined in this Appendix for integrating the lane resolution computation into the airborne and ground system; Section H.2 presents a typical technique.

H.1 GA1, GA2 NAVIGATION MANAGEMENT WORKLOAD

Several levels of automation were considered, beginning with the use of the aeronautical chart as the data reduction and information correlation device. Each aid to navigation was considered to have both a manual and an automatic position determination mode. Three sources of position determination information were considered: VOR/DME, NAV SAT, and LF Ground Based TD.

Communication workload was treated in a similar way, beginning with present-day voice communication and proceeding through an intermediate level of automation to a final,fully automatic data link.

In each case the ATC system relies upon a mixing of down-linked navigation data and present radar data for the generation of surveillance data. Nine of the configurations were assumed to interface with the ATC Flight Plan Reference System, which is a principal feature of the recommended system.

The candidate system levels of automation are tabulated in Table H-I.

The workload measurements were performed in the context of the Event Sequence Diagrams described in Appendix A. Because the candidate systems were only hypothetical, it was necessary to make assumptions about the related pilot's control-display device in order that task times might be estimated. Several of the panel configurations prepared for the workload measurements are included with this Appendix. See Figures H-1 . . . H-8.

Results of the workload measurements are summarized in Table H-II and discussed in Section 6 of this report.

TABLE H-1
GENERAL AVIATION (GA1, GA2) ADVANCED NAVIGATION/ TRAFFIC CONTROL SYSTEMS

USER	General Aviation System - Levels Of Automation	NAVIGATION							MAPS		COMPUTERS				COMMUNI-CATION			GROUND SYSTEM		
		UHF (VOR) NAV/COMM Receiver	UHF DME NAV Rec.	UHF NAV SAT Rec. - Manual Acq.	UHF NAV SAT Rec. - Auto Acq.	LF Ground Based TD Rec. - Manual Acq.	LF Ground Based TD Rec. - Auto Acq.	NAV SAT Ephemeris Data Tables	Local Aeronautical Chart	Local Aeronautical Chart - GB TD Contours	Hand Held DR Computation Aid	DR AT/CT Computer	GB TD Computer	Course Line Computer	VHF Voice Link	VHF Data Link - Min.	VHF Data Link - Max.	NAV SAT PF and Guidance, DR	GB TD PF and Guidance, DR	Storeable Flight Plan
GA1, GA2	g1			×				×	×		×				×			×		
GA1, GA2	g2				×			×	×		×				×			×		
GA1, GA2	g3					×				×	×				×				×	
GA1, GA2	g4						×			×	×				×				×	
GA1, GA2	g5				×			×	×		×				×			×		×
GA1, GA2	g6						×			×	×				×				×	×
GA2	g7				×			×	×		×				o	×		×		×
GA2	g8						×			×	×				o	×			×	×
GA2	g9				×				×			×			×	×		×		×
GA2	g10				×				×			×			o		×	×		×
GA2	g11						×			×			×		×	o				×
GA2	g12						×			×			×		o		×			×
GA2	g13	×	×						×						×					×
GA2	g14	×	×						×					×	o		×			×

x: Also used with navigation units g1, g2, g5 and g7

o: Voice as backup

1

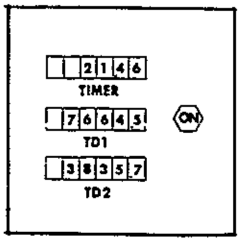


Figure H-1. Typical Control/Display for Systems g1, g2 and g5

2

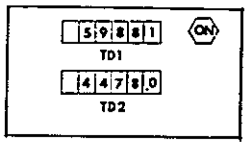


Figure H-2. Typical Control/Display for Systems g3, g4 and g6

3

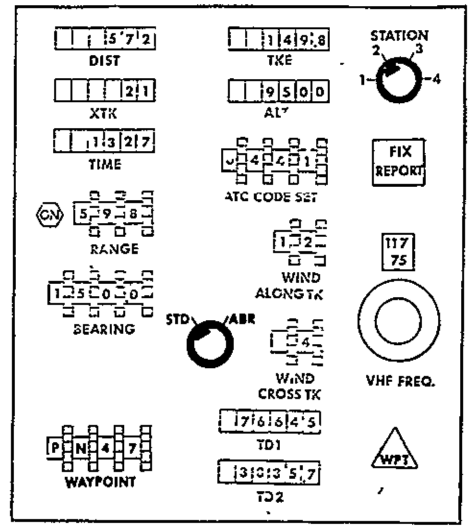


Figure H-3. Typical Control/Display for Systems g7 and g8

4

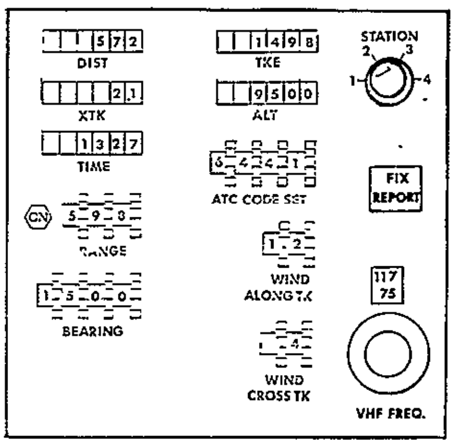


Figure H-4. Typical Control/Display for System g9

6

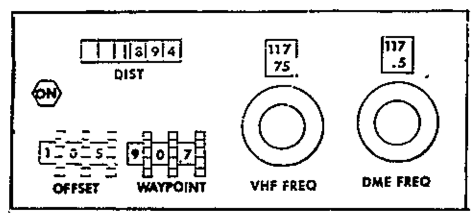


Figure H-6. Typical Control/Display for System g11

5

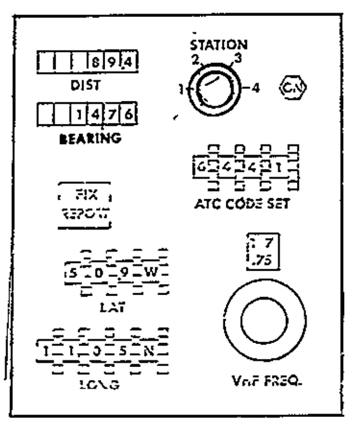


Figure H-5. Typical Control/Display for System g10

7

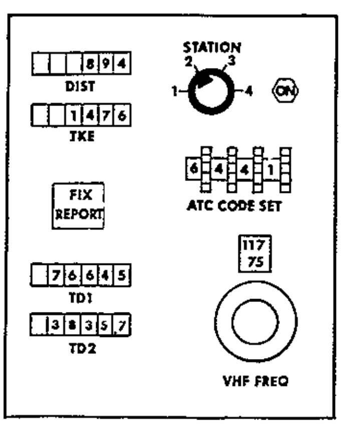


Figure H-7. Typical Control/Display for System g12

8

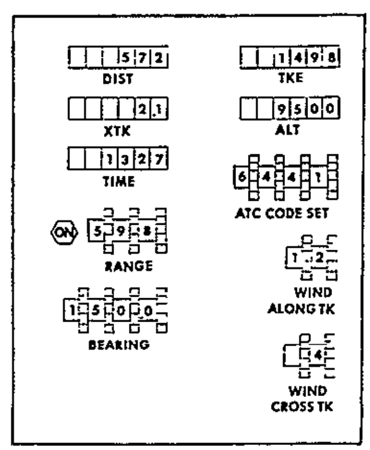


Figure H-8. Typical Control/Display for System g13 and g14

Figures H-1 . . . H-8. Typical Control/Display Configurations for Systems v1 . . . v14

TABLE H-II
NAVIGATION MANAGEMENT WORKLOAD ANALYSIS FOR GA1; GA2 AIRCRAFT

FLIGHT PHASE – VFR ENROUTE CONTROLLED AIRSPACE
– GENERAL AVIATION

Event: Single Leg NAV Management → ① **System g1**

UHF NAV SAT Receiver (Manual Acquisition)
NAV SAT Ephemeris Data Tables
Local Aeronautical Chart
Hand Held DR Computation Aid
VHF Voice Link
Ground System: Position Fix, Guidance and DR

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1 1	7
Estimate map position	10-30	8
Estimate NAV SAT ephemeris constants	5	8
Estimate time difference signals	10	8
Search, acquisition of TD signals	170	8
Maintain signal track	2	8
Review record, current leg, present status per report	22 8	8
Set direct comm frequency	2.1	7
*Request direct comm NAV SAT ATC center (A-G)	7.8	13
*Acknowledge direct comm. (G-A)	9.6	1
*Request NAV SAT position fix (A-G)	6.6	13
*Acknowledge request (G-A)	5 4	1
*State position estimate, way point/destination, TD1, TD2, Altitude, TAS, heading (A-G)	22.8	17
Receive range to way point, bearing to way point (G-A)	10.8	1
Steer revised course-------		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Steer revised course-------		
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6.2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δx, Δ fuel)	14.2	3
Correct steering, TAS, altitude-------		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report – standard (A-G)	29 4	17

Time = 657 sec   % Utilization Pilot 33 2

Event: Single Leg NAV Management → ② **System g2**

UHF NAV SAT Receiver (Automatic Search and Acquisition)
NAV SAT Ephemeris Data Tables
Local Aeronautical Chart
Hand Held DR Computer
VHF Voice Link
Ground System Position Fix, Guidance and DR

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Initiate search, acquisition, track	8.6	8
Estimate map position	10-30	8
Review record, current leg, present status per report	22.8	8
Set direct comm frequency	2.1	7
*Request direct comm NAV SAT ATC center (A-G)	7.8	13
*Acknowledge direct comm. (G-A)	9 6	1
*Request NAV SAT position fix (A-G)	6 6	13
*Acknowledge request (G-A)	5 4	1
*State position estimate, way point/destination, TD1, TD2, Altitude, TAS, heading (A-G)	22.8	17
Receive range to way point, bearing to way point (G-A)	10.8	1
Steer revised course-------		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Steer revised course-------		
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6 2	8
Plot cross track distance (map) and record	7 4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δx, Δ fuel)	14 2	3
Correct steering, TAS, altitude-------		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report – standard (A-G)	29.4	17

Time = 478 sec   % Utilization Pilot 35 0

*Communication Management Task

TABLE H-II (continued)
NAVIGATION MANAGEMENT WORKLOAD ANALYSIS FOR GA1, GA2 AIRCRAFT

FLIGHT PHASE – VFR ENROUTE CONTROLLED AIRSPACE
– GENERAL AVIATION

Event: Single Leg NAV Management → (3) **System g3**
LF Ground Based TD Receiver (Manual Acquisition)
Local Aeronautical Chart – GBTD Contours
Hand Held DR Computer
VHF Voice Link
Ground System Position Fix, DR, Guidance

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Estimate map position (range, bearing, from way point)	10-30	8
Estimate station locations	5	8
Select station on control panel	4.3	7
Estimate time difference from map	10	8
Search, acquisition of TD signals	170	8
Maintain signal track	2	8
Review record, current leg, present status per report	22.8	8
Set direct comm frequency	2.1	7
*Request direct comm GBTD ATC center (A-G)	7.8	13
*Acknowledge direct comm. (G-A)	9.6	1
*Request NAV SAT position fix (A-G)	6.6	13
*Acknowledge request (G-A)	5 4	1
*State position estimate, way point/destination, TD1, TD2, Altitude, TAS, heading (A-G)	22 8	17
Receive range to way point, bearing to way point (G-A)	10.8	1
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Steer revised course		
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6.2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δz, Δ fuel)	14.2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report – standard (A-G)	29.4	17

Time = 661 sec % Utilization Pilot 33.2

Event: Single Leg NAV Management → (4) **System g4**
LF Ground Based TD Receiver (Automatic Acquisition)
Local Aeronautical Chart with GBTD Contours
Hand Held DR Computer
VHF Voice Link
Ground System Position Fix, Guidance and DR

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Initiate search, acquisition, track	8.6	8
Estimate map position	10-30	8
Review record, current leg, present status per report	22.8	8
Set direct comm frequency	2.1	7
*Request direct comm ATC center (A-G)	7 8	13
*Acknowledge direct comm. (G-A)	9 6	1
*Request position fix (A-G)	6.6	13
*Acknowledge request (G-A)	5.4	1
*State position estimate, way point/destination, TD1, TD2, Altitude, TAS, heading (A-G)	22.8	17
Receive range to way point, bearing to way point (G-A)	10 8	1
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Steer revised course		
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6 2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δz, Δ fuel)	14 2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report – standard (A-G)	29.4	17

Time = 478 sec % Utilization Pilot 35.0

*Communication Management Task

TABLE H-II (continued)
NAVIGATION MANAGEMENT WORKLOAD ANALYSIS FOR GA1, GA2 AIRCRAFT

FLIGHT PHASE - VFR ENROUTE CONTROLLED AIRSPACE
- GENERAL AVIATION

Event: Single Leg NAV Management (5) → **System g5**

- UHF NAV SAT Receiver (Automatic Search and Acquisition)
- NAV SAT Ephemeris Data Tables
- Local Aeronautical Chart
- VHF Voice Link
- Ground System Position Fix, Guidance and DR
- Ground System Flight Plan Reference

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Initiate search, acquisition, track	8 6	8
Estimate map position	10-30	8
Review record, current leg, present status per report	22.8	8
Set direct comm frequency	2.1	7
*Request direct comm NAV SAT ATC center (A-G)	7.8	13
*Acknowledge direct comm. (G-A)	9 6	1
*Request NAV SAT position fix (A-G)	6 6	13
*Acknowledge request (G-A)	5 4	1
*State TD1, TD2.	9	17
Receive range to way point, bearing to way point (G-A)	10.8	1
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Steer revised course		
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6.2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1 2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δz, Δ fuel)	14.2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	29.4	17

Time = 464 sec   % Utilization Pilot 34 3

*Communication Management Task

Event: Single Leg NAV Management (6) → **System g6**

- LF Ground Based TD Receiver (Automatic Acquisition)
- Local Aeronautical Chart with GBTD contours
- VHF Voice Link
- Hand Held DR Computer
- Ground System Position Fix, Guidance, DR
- Ground System Flight Plan Reference

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Estimate map position (range, bearing, from way point)	10-30	8
Select chain on control panel	4 3	7
Initiate search, acquisition, track	8.6	8
Review record current leg, present status per report	22.8	8
*Set direct comm frequency	2.1	7
*Request direct comm ground based time difference ATC center (A-G)	7.8	13
*Acknowledge direct comm (G-A)	9.6	1
*Request GBTD position fix (A-G)	6.6	13
*Acknowledge request (G-A)	5.4	1
*State TD1, TD2	9	17
*Receive range to way point, bearing to way point (G-A)	10 8	1
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Steer revised course		
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6 2	8
Plot cross track distance (map) and record	7 4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4 3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δz, Δ fuel)	14.2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	29 4	17

Time = 468 sec   % Utilization Pilot 34.3

TABLE H-II (continued)
NAVIGATION MANAGEMENT WORKLOAD ANALYSIS FOR GA1, GA2 AIRCRAFT

FLIGHT PHASE – VFR ENROUTE CONTROLLED AIRSPACE
– GENERAL AVIATION

Event: Single Leg NAV Management (7)

System g7
- UHF NAV SAT Receiver (Automatic Search and Acquisition)
- NAV SAT Ephemeris Data Tables
- Local Aeronautical Chart
- Hand Held DR Computer
- VHF Voice Link (Back up)
- Minimum UHF Data Link (Primary)
- Ground System: Position Fix, Guidance, DR
- Ground System Flight Plan Reference

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Set satellite reference	4.3	8
Initiate search, acquisition, track	8.6	8
Set A/C code ident on UHF transponder	4.3	8
Set ATC code ident on UHF transponder	4 3	8
Set system for interrogation/or initiate fix command	1.1	7
*Receive NAV SAT data, TD1, TD2 every 12.4 sec (not displayed), dump upon interrogation A/C ident, ATC code, TD1, TD2 (A-G)	-	-
*Receive range to way point, bearing to way point (G-A) on display Read DTG, track angle	1 8	3
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Steer revised course		
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6.2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δr, Δ fuel)	14.2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	29 4	17

Time = 394 sec % Utilization Pilot 35 3

*Communication Management Task

Event: Single Leg NAV Management (8)

System g8
- VHF GB Time Difference Receiver (Automatic Search and Acquisition)
- Local Aeronautical Chart with GB TD Contours
- VHF Voice Link (Back up)
- Minimum VHF Data Link (Primary)
- Ground System: Position Fix, Guidance, DR
- Ground System: Flight Plan Reference

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1 1	7
Set chain	4 3	8
Initiate search, acquisition, track	8 6	8
Set A/C code ident. on VHF transponder	4 3	8
Set ATC code ident. on VHF transponder	4.3	8
Set system for interrogation/or initiate fix command	1.1	7
*Receive GBTD data TD1, TD2 continuously (not displayed), dump upon interrogation A/C ident., ATC code, TD1, TD2 (A-G)	-	-
*Receive range to way point, bearing to way point (G-A) on display. Read DTG, track angle	1.8	3
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Steer revised course		
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6 2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δr, Δ fuel)	14 2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	29 4	17

Time = 394 sec % Utilization Pilot 35 3

*Communication Management Task

TABLE H-II (continued)
NAVIGATION MANAGEMENT WORKLOAD ANALYSIS FOR GA1, GA2 AIRCRAFT

FLIGHT PHASE - VFR ENROUTE CONTROLLED AIRSPACE
- GENERAL AVIATION

Event: Single Leg NAV Management → **System g9** (9)

- UHF NAV SAT Receiver
- Local Aeronautical Charts
- DR AT/CT Computer
- VHF Voice Link (also Minimum data link)
- Ground System- Position Fix, Guidance
- Ground System: Flight Plan Reference

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
If System g2 - perform tasks to:		
Receive range to way point, bearing to way point (G-A)	95	8 5
If System g5 - perform tasks to:		
Receive range to way point, bearing to way point (G-A)	82	7.4
If System g7 - perform tasks to:		
Receive range to way point, bearing to way point (G-A) or display	25 5	7.6
Record DTG	5	7
Record course to way point	5	7
Steer revised course		
Enter range to way point	4.3	8
Enter bearing to way point	4 3	8
Enter cross track wind	4 3	8
Enter along track wind	4 3	8
Initiate AT/CT solution	1 1	7
Heading check and reset	5	8
Steer revised course		
Plot position on map	20	8
Track check and record		
Compute distance gone (map) and record	10	8
Record elapsed time	5	8
Record cross track distance	5	8
Ground speed check and record		
Compute ground speed	7	8
Read ground speed	1.1	3
Record ETA	5	8
Record ETE	5	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δz, Δ fuel)	14 2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	29.4	17

Time = 317 sec   % Utilization Pilot 36 2

*Communication Management Task

Event: Single Leg NAV Management → **System g10** (10)

- UHF NAV SAT Receiver (Automatic Search and Acquisition)
- Local Aeronautical Charts
- DR AT/CT Computer
- VHF Voice Link (Back up)
- Maximum VHF Data Link (Primary)
- Ground System Position Fix, Guidance
- Ground System- Flight Plan Reference

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1 1	7
Set satellite reference	4.3	8
Initiate search, acquisition, track	8.6	8
Set A/C code ident on UHF transponder	4 3	8
Set ATC code ident. on UHF transponder	4 3	8
Set system for interrogation/or initiate fix command	1.1	7
*Receive NAV SAT data, TD1, TD2 every 12 4 sec (not displayed), dump upon interrogation A/C ident, ATC code, TD1, TD2 (A-G)	-	-
*Receive range to way point, bearing to way point (G-A) on display. Read DTG, track angle	1.8	3
Steer revised course		
Enter range to way point	4 3	8
Enter bearing to way point	4 3	8
Enter cross track wind	4.3	8
Initiate AT/CT solution	1 1	7
Heading check and reset	5	8
Steer revised course		
Plot position on map	20	8
Track check and record		
Compute distance gone (map) and record	10	8
Record elapsed time	5	8
Record cross track distance	5	8
Ground speed check and record		
Compute ground speed	7	8
Read ground speed	1 1	3
Record ETA	5	8
Record ETE	5	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δz, Δ fuel)	14.2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	1.1	8

Time = 239 sec   % Utilization Pilot 36

*Communication Management Task

TABLE H-11 (continued)
NAVIGATION MANAGEMENT WORKLOAD ANALYSIS FOR GA1, GA2 AIRCRAFT

FLIGHT PHASE - VFR ENROUTE CONTROLLED AIRSPACE
- GENERAL AVIATION

Event: Single Leg NAV Management (11) → **System g11**

- LF Ground Based TD Receiver (Automatic Search and Acquisition)
- Local Aeronautical Charts, GB TD Contours
- Time Difference Computer
- Minimum VHF Voice Link
- Ground System: Flight Plan Reference

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Estimate map position	10	8
Set in master/slave station	4.3	8
Set A/C code in VHF transponder	4.3	8
Set ATC code in VHF transponder	4.3	8
Initiate search, acquisition, track	8.6	8
Insert present latitude estimate	4.3	8
Insert present longitude estimate	4 3	8
Insert way point latitude	4.3	8
Insert way point longitude	4.3	8
Initiate solution	1.1	8
Monitor DTG readout	1.1	3
Monitor course to steer readout	1.1	3
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Heading check and reset	5	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6.2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δz, Δ fuel)	14.2	3
Correct TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	29.4	17

Time = 315 sec   % Utilization Pilot 46.2

*Communication Management Task

Event: Single Leg NAV Management (12) → **System g12**

- LF Ground Based TD Receiver (Automatic Search and Acquisition)
- Local Aeronautical Charts, GB TD Contours
- Time Difference Computer
- VHF Voice Link (Back up)
- Maximum VHF Data Link (Primary)
- Ground System Flight Plan Reference

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Estimate map position	10	8
Set in master/slave station	4.3	8
Set A/C code in VHF transponder	4 3	8
Set ATC code in VHF transponder	4 3	8
Initiate search, acquisition, track	8 6	8
Insert present latitude estimate	4.3	8
Insert present longitude estimate	4.3	8
Insert way point latitude	4.3	8
Insert way point longitude	4.3	8
Initiate solution	1.1	8
Monitor DTG readout	1.1	3
Monitor course to steer readout	1 1	3
Set system for interrogation/or initiate report	1.1	8
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Heading check and reset	5	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6.2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δz, Δ fuel)	14.2	3
Correct TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	1.1	8

Time = 328 sec   % Utilization Pilot 34

TABLE H-II (continued)
NAVIGATION MANAGEMENT WORKLOAD ANALYSIS FOR GA1, GA2 AIRCRAFT

FLIGHT PHASE - VFR ENROUTE CONTROLLED AIRSPACE
- GENERAL AVIATION

Event (13): Single Leg NAV Management

System g13:
- VHF VOR Nav/Comm Receiver
- UHF DME Transmitter/Receiver
- Local Aeronautical Chart
- Course Line Computer
- VHF Voice Link
- Ground System: Storeable Flight Plan

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1.1	7
Select way point from map	10	8
Select and set VOR frequency	4.3	8
Select and set DME frequency	4.3	8
Measure range - VOR/DME to way point	5	8
Measure bearing - VOR/DME to way point	5	8
Set range	4.3	8
Set bearing	4 3	8
Monitor DTG readout	1.1	3
Monitor course to steer readout	1.1	3
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6 2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1.2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δε, Δ fuel)	14.2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	29 4	17

Time = 410 sec   % Utilization Pilot 35.2

*Communication Management Task

Event (14): Single Leg NAV Management

System g14:
- VHF VOR Nav/Comm Receiver
- UHF DME Transmitter/Receiver
- Local Aeronautical Chart
- Course Line Computer
- VHF Voice Link (Back up)
- Maximum VHF Data Link (Primary)
- Ground System Storeable Flight Plan

Task	Time	Utilization Factor
Review current met forecast	30-300	8
Switch-on	1 1	7
Select way point from map	10	8
Select and set VOR frequency	4.3	8
Select and set DME frequency	4.3	8
Set A/C code ident on VHF transponder	4.3	8
Set ATC code ident on VHF transponder	4 3	8
Measure range - VOR/DME to way point	5	8
Measure bearing - VOR/DME to way point	5	8
Set range	4.3	8
Set bearing	4 3	8
Monitor DTG readout	1 1	3
Monitor course to steer readout	1.1	3
Set system for interrogation	1.1	8
Steer revised course		
Record DTG	5	7
Record magnetic bearing to way point	5	7
Plot position on map	20	8
Recalculate drift angle	45	8
Heading check and reset	5-60	8
Track check and record	5	8
Compute distance gone (map) and record	10-30	8
Read and record elapsed time	6.2	8
Plot cross track distance (map) and record	7.4	8
Ground speed check and record	5	8
Compute ground speed	7	8
Read TAS	1 2	3
Estimate tailwind component	10	8
Course to steer check and record	5	8
Compute course less drift angle (track angle)	4.3	8
ETA check and record	10	8
ETE check and record	10	8
Flight level check, monitor and reset pressure reference	6.7	8
Fuel check and record	10	8
Flight plan status check (DTG, ΔETA, ΔGS, ΔCT, Δε, Δ fuel)	14.2	3
Correct steering, TAS, altitude		
Update met forecast	60	17
Prepare and record flight log (above)	-	-
Prepare ATC report	60	8
*Release Report - standard (A-G)	1 1	8

Time = 478 sec   % Utilization Pilot 31.8

*Communication Management Task

H.2 THE AMBIGUITY RESOLUTION OF TIME DIFFERENCE/CONTINUOUS WAVE SYSTEMS (TD/CW)

General aviation systems g4, g6 and g8 are promising area navigation systems which present solutions for the general aviation problem. The system transmits time difference data to the ground system, and returns guidance information on the uplink.

A major problem area in the operation of a CW time difference system is the resolution of the ambiguities in the TD measurements. The following discussion outlines an operational procedure for ambiguity resolution, using a dead reckoning computer and ATC surveillance information.

H.2.1 Summary

An operational procedure for ambiguity resolution is presented in the form of a functional sequence diagram (FSD). An FSD of a particular task presents the following information:

(1) Information flow between components
(2) Component interaction
(3) Component functions
(4) Procedure for performing task
(5) Logic for performing task

H.2.2 Ambiguity Resolution (See Figure H-9)

The ambiguities in the CW/TD system arise when an aircraft loses the TD signals for some period of time, or when an aircraft leaves the coverage of one chain and enters the service area of a second chain.

The principal aids for ambiguity resolution are the dead reckoning sensors of the aircraft. They are assumed to be input into a dead reckoning computer. During nominal operation, a TD input is also available to the DR computer so that the DR position can be updated and malfunctions of the TD subsystem or the DR subsystem can be detected. Through interactions with the TD computer, TD coordinates are computed from the DR position and the lane counters are set by the pilot. Should the DR position differ from the TD position by a specified error limit, the conflict is resolved by requesting an ATC surveillance check. If the conflict still persists, the procedure may be recycled or it may be found that the TD receiver is inoperable.

The FSD is presented for an aircraft with an onboard computer for TD position fixing. A similar procedure could be utilized by an aircraft with no TD computer but with a DR computer and a data link to a ground based computer.

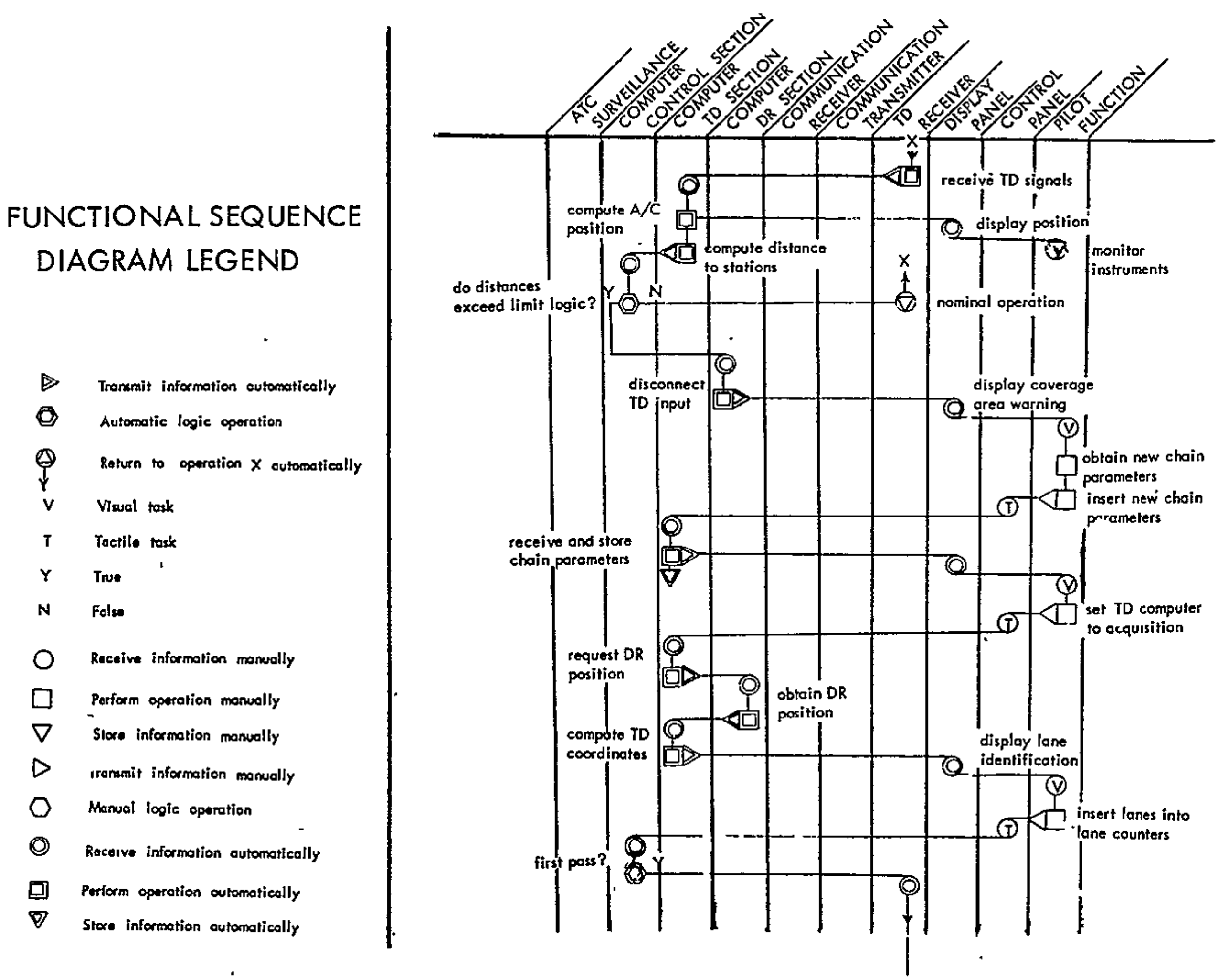


Figure H-9. Ambiguity Resolution - Functional Sequence Diagram
(continued on Page H-14)

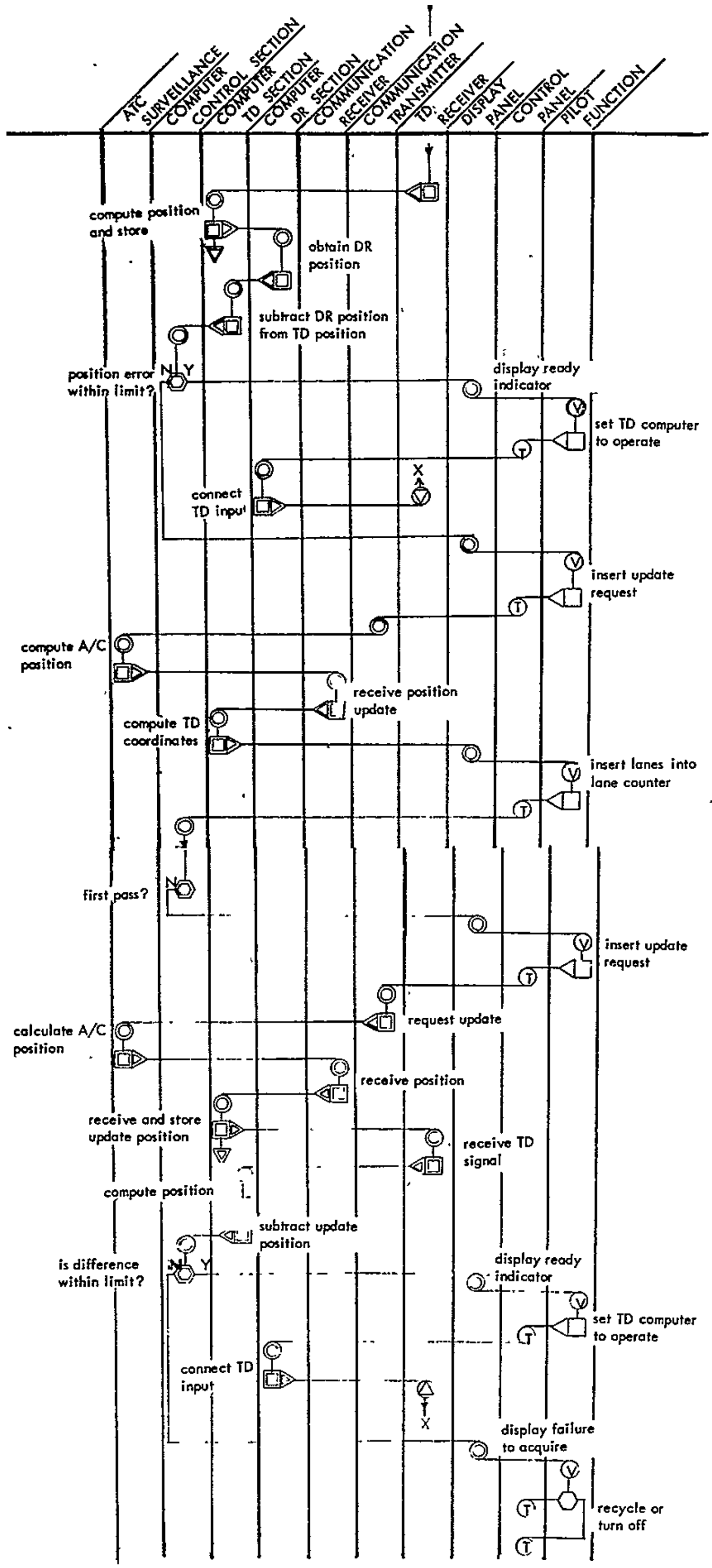


Figure H-9 (cont'd). Ambiguity Resolution Functional Sequence Diagram

H.3 NAVIGATION COMPUTER PROGRAM REQUIREMENTS FOR GENERAL AVIATION CATEGORY - HYPERBOLIC COORDINATE CONVERTER, DEAD RECKONING SYSTEM

In this Appendix, H, the algorithms needed to solve the coordinate conversion problem and dead reckoning problem are developed. These algorithms are then programmed using a hypothetical machine language that is representative of languages common to most airborne digital computers.

The object is to estimate the amount of storage needed (i.e., "size" of the computer) and provide a means for estimating the time of execution.

H.3.1 Hyperbolic Coordinate Conversion

This problem can be separated into two parts: (1) the transformation of hyperbolic time difference signals into latitude and longitude; and (2) the conversion of latitude and longitude into information relative to a specified track. Systems g11 and g12 require this capability.

H.3.1.1 Hyperbolic Coordinate Conversion to Latitude and Longitude

Several different solutions to the hyperbolic conversion problem have been developed. The drawback of most is that they are iterative solutions which can be very time consuming on a computer. However, an explicit solution [Ref 62] has been developed which, in addition to being noniterative, includes corrections for the non-spherical earth (Clarke-Spheroid of 1866). This is obtained by using an osculating sphere, tangent to the spheroid at the aircraft position, whose radius equals the radius of curvature at that point.

A flow chart, Figure H-10, shows the equations. The pertinent variables are:

r - Index of refraction

v_o - Velocity of light in vacuum

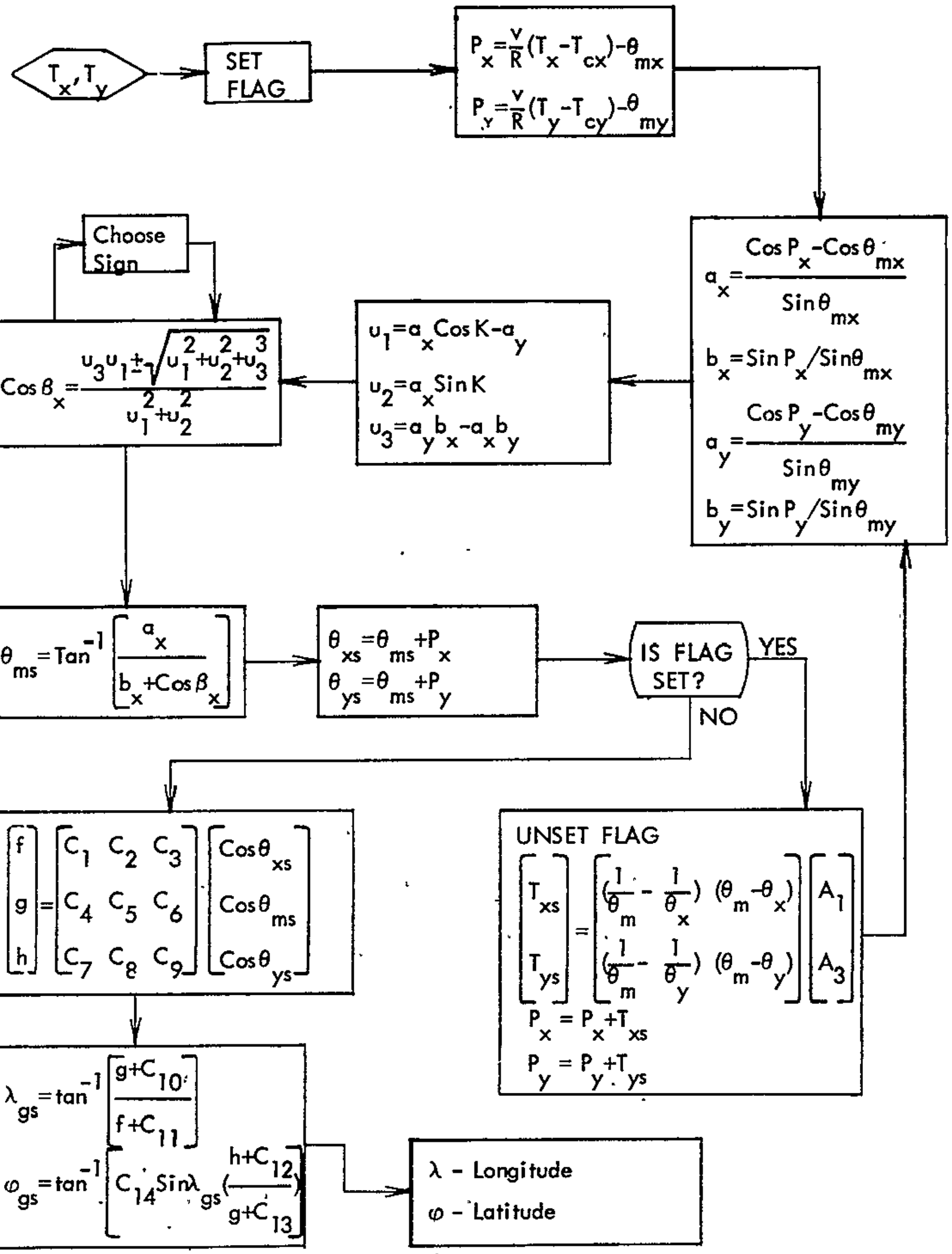


Figure H-10. Time Difference Coordinate Conversion

v - Actual velocity of light

X - X-slave station

Y - Y-slave station

M - Master station

S - Receiver

T_{ci} - i-slave coding delay, if any

T_i - i-slave time difference

θ_{mi} - i-slave baseline arc

K - angle between baseline arcs

β_i - angle between i-slave baseline arc and arc from Master to Receiver

θ_{ms} - arc from Master to Receiver

θ_{is} - arc from i-slave to Receiver

T_{is} - secondary phase correction associated with i-slave and Receiver

A1, A3- constant for determining secondary phase correction

λ - Longitude

ϕ - Latitude

C_1-C_{14} Constants (function of chain geometry, etc.)

The computer solution to this flow chart is expressed as a step by step set of equations, with running explanations. But this is only one part of the entire program, the other parts being system set-up (where all fixed inputs are read), logic, along-cross-track conversion, flight plan conversion, and track set-up. Part of this hyperbolic to lat/long routine is executed only once for a given station chain, and so is in the system set-up routine.

H.3.1.2 Conversion To Along-Cross-Track Coordinates

The desired outputs are range and bearing to a specific waypoint. These are obtained by first solving assuming a spherical earth and then making corrections. The spherical trigonometric equations for range angle and bearing are:

$$B = \mathrm{Cos}^{-1}\left[\mathrm{Sin}\,X_m\,\mathrm{Sin}\,X_n + \mathrm{Cos}\,X_m\,\mathrm{Cos}\,X_n\,\mathrm{Cos}(Y_m - Y_n)\right]$$

$$A = \mathrm{Sin}^{-1}\left[\mathrm{Cos}\,X_m\,\mathrm{Sin}(Y_m - Y_n) / \mathrm{Sin}\,B\right]$$

where

$X_n, Y_n,$ - Lat and Long of A/C position
$X_m, Y_m,$ - Lat and Long of waypoint
B - Range angle
A - Bearing angle (referred to North)

An example correction equation (for range) is:

ϕm = mean latitude
a, b = equatorial, polar radii
$$\text{Range} = ab\,B / (a^2\,\mathrm{Sin}^2\phi_m + b^2\,\mathrm{Cos}^2\phi_m)^{1/2}$$

It is assumed that a similar type of correction may be made for bearing angle. Again, this routine is not written in machine language, but as step by step equations.

H.3.1.3 Develop Flight Plan Track

When operating in Flight Plan mode, the operator desires cross-track deviation (CTD) and distance gone (DG) about a specified track. Otherwise, he is in the Steering mode, and has as outputs range and bearing to the waypoint (WP). So when Flight Plan operation is desired, Switch 2 is in the Off (Flight Plan) position, which causes two inputs to be read, latitude and longitude, of the start point (SP). The tangents of these angles are found, and the TRACK CONVERSION routine is run, and the resulting range and bearing are stored separately as the flight plan track.

H.3.1.4 Flight Plan Conversion

This routine operates after every execution of the HYPERBOLIC and TRACK routines when in flight plan mode. Its purpose is to convert range and bearing to waypoint information to cross track deviation and it should be noted that if the operator sets up in flight plan mode, then he may switch between the two modes at will during operation to read both sets of outputs.

The functions of the three switches are:

SW0: OFF - Ready; ON - Chain Parameter Input

SW1: OFF - Area Parameter, Waypoint Input; ON - Operate

SW2: OFF - Flight Plan Mode; ON - Steering Mode

H.3.1.5 Storage Requirements and Execution Times

Total Program Storage Requirements

Routine	Instructions	Variable Data	Permanent Data	
Hyperbolic Conversion	203	16	1	
Track Conversion	127	8		
Flight Plan Conversion	32	8	5	
Chain Load	60	28	1	
Waypoint Load, Operation	71	18	2	
Other	6	—	6	
	499	78	15	= 592
+ Square Root Subroutine	30	3	4	
	529	81	19	= 629
+ Trigonometric Subroutine	100	15	28	
	629	96	47	= 772

Total Machine Operations For Set-Up

Routine	Add	Mult.	Div.	Jump	Mem.	Words	Trig.	Sq. Rt.
Chain Load	3	3	2	6	34	60	3	3
W.P. Load	8	8	12	19	25	147	4	4
Track Conv.	19	20	7	2	23	127	2	5
	30	31	21	27	82	334	9	12
+ Sq. Rt. (12)	264	60	60	132	300	1176	—	-12
	294	91	81	159	382	1510	9	0
+ Trig. (9)	270	63	0	90	540	900	-9	—
	564	154	81	249	922	2410	0	0

Total Machine Operations For One Cycle (Flight Plan Mode)

Routine	Add	Mult.	Div.	Jump	Mem.	Words	Trig.	Sq. Rt.
Hyperbolic	42	41	18	5	62	281	8	7
Track	19	20	7	2	23	127	2	5
Flight Plan	4	7	1	1	12	32	—	1
	65	68	26	8	97	440	10	13
+ Sq. Rt.	286	65	65	143	325	1274	0	-13
	351	133	91	151	422	1714	10	0
+ Trig.	300	70	0	100	600	1000	-10	0
	651	203	91	251	1022	2714	0	0

Time Computations for Two Typical but Very Different Types of Computers:

Decca Omnitrac IIb; LSI DIVIC

Omnitrac:	Add	Mult.	Div.	Jump	Mem.	Words
Time (μs):	84	1,292	2,000	84	84	84
Ops:	54,684	262,276	182,000	21,084	85,848	227,976

Total = 0.834 sec/cycle

DIVIC:	Add	Mult.	Div.	Jump	Mem.	Words	Trig.
Time (μs):	12	108	360	12	12	12	360
Ops:	4,212	14,364	32,760	1,812	5,064	20,568	3,600

Total = 0.082 sec/cycle

H.3.2 Dead Reckoning Computer, System g9, g10

This computer would take inputs of range and bearing to a destination (waypoint), and from the inputs, wind vector, airspeed, altitude, pitch angle and compass direction, compute outputs of ground speed, distance to go, cross track deviation, course to steer, altitude and time to go. The range and bearing inputs would come from a navigation aid such as satellites, or from hand calculations.

H.3.2.1 Inputs and Outputs

The inputs may be broken down in the following manner:

Automatic (or manual insert):

- DTG_o - Range to destination
- A_{to} - Bearing to destination

Manual Insert:

- V_{WAT} - Wind component, along track
- V_{WCT} - Wind component, cross track
- Z_A(SET) - Pressure correction

Sensor Information:

- V - Airspeed
- Z_A - Altitude
- p - Pitch angle
- A - Compass heading

The outputs are:

- GS - Ground speed
- TTG - Time to go
- DTG - Distance to go
- δ - Cross track deviation
- α - Course to steer
- Z_A - Altitude

H.3.2.2 Equations For Dead Reckoning

$$Z_A = Z_A + Z_A(SET)$$

$$X_{AT} = \int_{t_o}^{t} (V_{WAT} + V \cos (A_{to} - A) \cos p)\, dt$$

$$Y_{AT} = \int_{t_o}^{t} (V_{WCT} + V \sin (A_{to} - A) \cos p)\, dt$$

X_{AT} = distance traveled along track

Y_{CT} = distance traveled cross track

$$DTG = [(DTG_o - X_{AT})^2 + (Y_{AT})^2]^{1/2}$$

$$\delta = Y_{CT}$$

$$\alpha = A_{to} - A + \sin^{-1} \left(\frac{Y_{CT}}{DTG} \right)$$

$$GS = V \cos p + V_{WAT}$$

$$TTG = DTG/GS$$

The integrations are accomplished by a summation for each cycle of the program. The time of each cycle is stored as a constant. The cycle time is multiplied by the expression within the integral and added to the running sum. For example,

$$X_{AT} = \sum_{n=1}^{t/\Delta t} [V_{WAT} + V_N \cos (A_{to} - A_n) \cos p_n] \; \Delta t$$

(Δt = cycle time)

H.3.2.3 Storage Requirements and Operating Times

Storage Requirements

Routine	Instructions	Variable Data	Permanent Data	
Program	78	12	2	= 90
+ Square Root Subroutine	30	3	4	
	108	15	6	= 129
+ Trigometric Subroutine	112	15	28	
	220	30	34	= 284

Total Machine Operations for Each Cycle

Routine	Add	Mult.	Div.	Jump	Mem.	Words	Trig	Sq. Rt.
Main	10	9	3	6	24	70	3	2
+ Sq. Rt. (2)	44	10	10	22	50	196	0	-2
	54	19	13	28	74	266	3	0
+ Trig. (3)	90	21	0	30	180	300	-3	0
	144	40	13	58	154	566	0	0

Omnitrac:	Add	Mult.	Div.	Jump	Mem.	Words
Time (μs):	84	1,292	2,000	84	84	84
Ops:	12,096	51,680	26,000	4,872	21,336	47,544

Total = 0.164 sec/cycle

DIVIC:	Add	Mult.	Div.	Jump	Mem.	Words	Trig
Time (μs):	12	108	360	12	12	12	360
Ops:	648	2,052	4,680	336	888	3,192	1,080

Total = 0.0129 sec/cycle

APPENDIX I

NEW TECHNOLOGY

In compliance with the New Technology clause (May 1966) of the subject contract, this Appendix K has been included. Although the subject matter of this contract is particularly analytical in nature, it is felt that some of the concepts advanced in this report are unique, and could be construed as falling in the category of new technology in its broadest sense.

Given the scope of the NAVTRACS program and the overall requirement to evaluate advanced navigation/traffic control concepts from the user viewpoint in an advanced time frame, a page-by-page identification of new technology content in this report was not considered practical. Where pertinent, identification has been made on a sectional basis.

(1) One project task undertaken during this program was the concept formulation and system synthesis of an advanced navigation/traffic control system employing area navigation for all user aircraft including general aviation, VTOL, STOL, SST, and CTOL jet aircraft. Sections 4.1, 4.3 and 4.4 describe the Flight Plan Reference airborne subsystem. Section 4.5 describes the Flight Plan Reference ground system. While not specifically representing new technology in its strictest sense, it is felt that the overall Flight Plan Reference concept of navigation/traffic control is a major essential element of any new ATC system concept. As developed in the course of this study, proper implementation of this concept could have a dramatic effect on the future of air transportation in this country.

(2) In conjunction with the concept of Flight Plan Reference, the use of the concept of airborne and ground based Limit Logic computations, described in Section 4.1, provides an even more effective tool in reducing pilot and controller workload and communications, resulting ultimately in a greater capacity of the future traffic control system.

(3) The results of the NAVTRACS program were derived through the use of a specific, large scale, man-machine methodology. Sections 2 through 7 and Appendix A summarize this technique, which is unique for the synthesis of navigation/traffic control systems from the viewpoint of the pilot. Additional studies and evaluations in this general area could make significant use of this methodology.

REFERENCES

1. "Independent Surveillance and Communication Using Satellites," N68-24501, August 1967.
2. "Preliminary Report on the SOA of Omega," N67-10030, August 1966.
3. "Second Report on Omega, Differential Omega and OPLE," N68-23973, April 1968.
4. "Transmission of Characteristic Data and Range Measurement in ATC," N67-18445, 1965.
5. "Alternative Approaches for Reducing Delays in Terminal Areas," N68-12177, November 1967.
6. "The Current State of the SUD-LEAR Programme to Reduce Landing Minima and Develop an All-Weather Landing System," N68-11611, 1965.
7. "Study on the Feasibility of V/STOL Concepts for Short-Haul Transport Aircraft," NASA CR-670, January 1967.
8. "Feasibility on V/STOL Concepts for Short-Haul Transport Aircraft," NASA CR-743, May 1967.
9. "Supplement to Feasibility on V/STOL Concepts for Short-Haul Transport Aircraft," NASA CR-743(1), September 1968.
10. "Empirical Human-Factors Investigation of Display Design," N67-29922, April 1967.
11. "Jets in a Horse and Buggy Era," N67-22270, December 1966.
12. "Meeting the Problems of Success," N67-22268, December 1966.
13. "Airborne Radar for Helicopter Navigation," N67-27193, September 1966.
14. "Dallas/Ft. Worth Regional Airport Simulation Study," N67-27188, April 1967.

15. "Technical and Economic Evaluation of Aircraft for Intercity Short-Haul Transportation," Vol. I, N67-10599, April 1966.

16. "Technical and Economic Evaluation of Aircraft for Intercity Short-Haul Transportation," Vol. II, N67-10595, April 1966.

17. "Technical and Economic Evaluation of Aircraft for Intercity Short-Haul Transportation," Vol. III, N67-12024, April 1966.

18. "Study of the Optimum Values of Several Parameters Affecting Longitudinal Handling Qualities of VTOL Aircraft," NASA TN D-4624, July 1968.

19. "Aviation and the Transportation System," N67-22267, February 1967.

20. "Final Report: Field Appraisal of the Advanced Radar Traffic Control System, [ARTS]," N68-13946, October 1967.

21. "Field Appraisal of the Advanced Radar Traffic Control System - Appendix," N68-13945, October 1967.

22. "OPLE Experiment," N67-36634, June 1967.

23. "Weather Conditions Affecting VTOL Operations in the Northeast Corridor," N68-11922, November 1966.

24. "Crab Angle Sensing System," N68-15233, November 1967.

25. "Technological Gaps in V/STOL Development," N68-12964, October 1967.

26. "Factors Influencing the Choice of Facilities and Techniques for Aeronautical Development," N68-25578, April 6, 1967.

27. "Simulation Technology," N68-22824, April 1967.

28. "Proposed Analytical Model for the Final Stages of Landing a Transport Airplane," NASA TN D-4438, June 1968.

29. "Summary of VGH Data . . . . . Airline Operations," NASA TN D-4529, May 1968.

30. "Trends in Repeated Loads on Transport Airplanes," NASA TN D-4586, May 1968.

31. "Simulation Studies of the SST in the Present-Day ATC System," NASA TN D-4638, July 1968.

32. "A Simulator Study of a Pictorial Navigation Display in Instrument Departure of the SST," NASA TN D-4029, July 1967.

33. "ATC Concepts for Supersonic Vehicles - Part I," N67-13246, August 1966.

34. "ATC Concepts for Supersonic Vehicles - Part II-1," N67-38953, August 1967.

35. "ATC Concepts for Supersonic Vehicles - Part II-2," N68-13158, November 1967.

36. "An Experimental Investigation of Compensatory and Pursuit Tracking Displays with Rate and Acceleration Control Dynamics and a Disturbance Input," NASA CR-1082, June 1968.

37. "Some Studies Into Improvements in Automatic Throttle Control," N68-13060, September 1967.

38. "The Pilot's Safety Problem in CAT II Operations and the Potential Contribution of HUD," N68-12865, June 1966.

39. "The Effect of Low Altitude Gusts on Automatic Landing," N68-25286, September 1966.

40. "Avionics Requirements for All-Weather Landing of Advanced SST's," N67-28753, April 1967.

41. "All-Weather Landing Simulation for CAT III, Airborne Configuration," Vol. I, N68-12238, July 1967.

42. "All-Weather Landing Simulation for CAT III Airborne Configuration," Vol. II, N67-39703, July 1967.

43. "New York Interim Common Tracon Facility Simulation Study," N67-10448, October 1967.

44. "Evaluation of a High-Gain VHF/UHF Communication Facility," N67-39295, July 1967.

45. "Human Factors Evaluation of a Large Screen Radar Display," N67-27189, March 1967.

46. "Cockpit Instrumentation and Layout," IATA, May 1960.

47. "Analysis of Control-Display Limitations in Multi-Jet Transport Aircraft," GGC/EE/64-4, June 1964.

48. "The Allotment of Probability Shares," Memo PE-18, April 1966.

49. "Navigation Management Operational Study-Civil Air Transport Application," Polhemus Associates, Lear Seigler Inc., October 1966.

50. Journal of the Institute of Navigation, Vol. 15, No. 2, Summer 1968.

51. "The Requirement for Height Measurement in the SST," ION-British, January 1966.

52. "Study of a Navigation and Traffic Control Technique Employing Satellites," TRW 08710-6015-R000, December 1967.

53. Glen M. Harold, "Trends in Computer Technology," presented at the 24th Annual Meeting, Institue of Navigation, Monterey, California, June 19-21, 1968.

54. "Recent Advances in Display Media," NASA SP-159, 1968.

55. "Peripheral Vision Displays," NASA CR-808, June 1967.

56. "Take-Off Tests on a Transport Aircraft Including the Use of a 'SCAT' Take-Off Director," N68-24790, 1968.

57. "Aviation Demand and Airport Facility Requirement Forecasts for Large Air Transportation Hubs through 1980," N68-10267, August 1967.

58. "A Digital System for Position Determination," reprint from IRE Transaction of the PG SET, Vol. SET-5, No. 1, March 1959.

59. "Automatic Landing - Recent R.A.E. Contributions," N67-29925, October 1967.

60. "SST ATC Simulation Trials," TEU/S2;028, August 1967.

61. "Comparison of Information Display Concepts for Landing of VTOL Aircraft," NASA TN D-4861, November 1968.

62. "A Simulator Investigation of the Problems of Visual Taxi Guidance in Low Visibilities," N68-21987, August 1967.

63. "KLM-Research on the Lowering of Weather Minima for Landing of Aircraft," N68-12794, August 1967.

64. "Preliminary Quantitative Analysis of Airborne Weather Radar," N68-15598, December 1967.

65. "Cost/Benefit Analysis for All-Weather Landing System (AWLS) - CAT II and III," N68-12879, October 1967.

66. "Enroute IFR Air Traffic Relationships," N68-14021, November 1967.

67. "Tactical V/STOL Weapon System Control Display Requirements Study for the Navigator's Station," PAI-TR-66-2, July 1966.

68. "SOA for V/STOL Control Display," RTD-TDR-63-4167, October 1963.

69. "Preliminary V/STOL Control-Display Subsystem Requirements Study," FDL-TDR-64-85, June 1964.

70. "Navigation/Traffic Control Satellite Mission Study," Technical Proposal Document P-67061, June 8, 1967.

71. "Third Annual NASA-University Conference on Manual Control," NASA SP-144, USC, Los Angeles, California, March 1-3, 1967.

72. Survey Officer's Manual, "The Application of LORAC to Precision Terrestial Line-Length Measurement and Position Fixing," AD 232 017 (no date)

73. "Satellite Navigation Studies Progress Report - 10/1/65 - 9/30/66," Contract No. NASr-54(10), May 1967.

74. "Phase Difference Navigation Satellite Study," N67-34257, June 1967.

75. "A Descriptive Model for Determining Optimal Human Performance in Systems," Vol. III, CR-878, March 1968.

76. D. T. McRuer and E. S. Krendel, "Dynamic Response of Human Operators," USAF WADC TR 56-524, 1957.

77. "Extract of the Study about Potential Roles of SST Crews and Some Implications of the Flight Deck," NASA CR-561, undated.

78. Sheldon Razin, "Explicit (Noniterative) Loran Solution," Navigation, Fall 1967, Vol. 14, No. 3.

79. "Application of the Airborne General Purpose Digital Computer in Air Data Systems," Appendix A - Computer Survey, Polhemus Associates, Inc., 1967.

80. World Distribution and Characteristics of Atmospheric Radio Noise, Report No. 322, Documents of the Xth Plenary Assembly of the International Radio Consultative Committee at Geneva, 1963, International Telecommunication Union, Geneva, 196

81. A. D. Watt and R. W. Plush, "Power Requirements and Choice of an Optimum Frequency for a Worldwide Standard-Frequency Broadcasting Station," Journal of Research, National Bureau of Standards, Vol. 63D, No. 1, July-August 1959, pp. 35-44.

82. E. R. Swanson, "VLF Radio Navigation Systems," Modern Navigational Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conference, Ann Arbor, July 22-August 2, 1968.

83. J. A. Pierce, "Intercontinental Frequency Comparison by Low-Frequency Radio Transmission," Proc. IRE, Vol. 45, No. 6, June 1957, pp. 794-803.

84. W. L. Taylor, "VLF Attenuation for East-West and West-East Daytime Propagation Using Atmospherics," Journal of Geophysical Research, Vol 65, No. 7, July 1960, pp. 1933-1938.

85. J. E. Howell, "Geodetic Secor," presented at the XIV Symposium of the Avionics Panel of the Advisory Group for Aerospace Research and Development (AGARD-NATO) on Advanced Navigational Techniques, Milan, Italy, September 12-15, 1967.

86. J. R. Johler, W. J. Kellar and L. C. Walters, Phase of the Low Radio-frequency Ground Wave, National Bureau of Standards Circular 573, U. S. Department of Commerce, Washington, D. C., June 26, 1956.

87. C. Williams, "Low Frequency Radio Wave Propagation by the Ionosphere with Particular Reference to Long-Distance Navigation," Proc. I.E.E., 98, Part III, March 1951, pp. 81-103.

88. R. E. Scott, "Low Frequency Propagation," Modern Navigational Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conference, Ann Arbor, July 22-August 2, 1968, Chapter 15.

89. J. R. Johler and L. A. Berry, Loran-D Phase Corrections Over Inhomogeneous, Irregular Terrain, ESSA Technical Report IER 59 - ITSA 56, Institute for Telecommunication Sciences and Aeronomy, Boulder, Colorado, November 1967.

90. James R. Wait, "Amplitude and Phase of the Low-Frequency Ground-Wave Near a Coastline," Journal of Research, National Bureau of Standards, Vol 58, No. 5, May 1957.

91. J. O'Day, "Errors in the Field of a Low Frequency Hyperbolic Navigation System in Mountainous Terrain," Modern Navigational Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conference, Ann Arbor, July 22-August 2, 1968, Chapter 26.

92. R. A. Volz, "Application of Correlation and Measurement Techniques to the Calibration of Errors in Low-Frequency Navigation Systems," Modern Navigational Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conference, Ann Arbor, July 22-August 2, 1968, Chapter 25.

93. Final Report of the Ad Hoc Joint Navigation Satellite Committee, May 1966.