GUIDANCE, NAVIGATION, AND CONTROL 2015

Edited by
Ian J. Gravseth

American Astronautical Society

Volume 154

ADVANCES IN THE ASTRONAUTICAL SCIENCES

GUIDANCE, NAVIGATION, AND CONTROL 2015

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Front Cover Illustration:

NASA's Chandra X-ray telescope has made the first detection of X-ray emission from young solar-type stars that lie outside our Milky Way galaxy. They live in a region known as the "Wing" of the Small Magellanic Cloud, a satellite galaxy of our Milky Way. X-ray data indicates the activity level of the magnetic fields, which provides clues to a star's rotation rate and the rising and falling of hot gas in the star's interior. In this composite image from NASA's Great Observatories of the Wing, the Chandra data are shown in purple; visible light seen by the Hubble Space Telescope is in red, green, and blue; and infrared data from the Spitzer Space Telescope are colored red. Credit: NASA, ESA, CXC, and the University of Potsdam, JPL-Caltech, and STScI.

Frontispiece:

This picture shows JPSS during integration at Ball Aerospace & Technologies Corp. JPSS is the nation's next generation polar-orbiting operational environmental satellite system. It is scheduled to launch in mid-2017, and will provide data critical to forecasting weather through 2025. Once operational, it will provide global measurements of atmospheric, terrestrial and oceanic conditions, including sea and land surface temperatures, vegetation, clouds, rainfall, snow and ice cover, fire locations and smoke plumes, atmospheric temperature, water vapor and ozone. JPSS delivers key observations for the nation's essential products and services, including forecasting severe weather like hurricanes, tornadoes and blizzards days in advance, and assessing environmental hazards such as droughts, forest fires, poor air quality and harmful coastal waters. Credit: Ball Aerospace & Technology Corp.

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FOREWORD

HISTORICAL SUMMARY

The annual American Astronautical Society Rocky Mountain Guidance and Control Conference began as an informal exchange of ideas and reports of achievements among local guidance and control specialists. Since most area guidance and control experts participate in the American Astronautical Society, it was natural to gather under the auspices of the Rocky Mountain Section of the AAS.

In the late seventies, Bud Gates, Don Parsons and Sherm Seltzer, collaborating on a guidance and control project, met in the Colorado Rockies for a working ski week. They jointly came up with the idea of convening a broad spectrum of experts in the field for a fertile exchange of aerospace control ideas, and a concurrent ski vacation. At about this same time, Dan DeBra and Lou Herman discussed a similar plan while on vacation skiing at Keystone.

Back in Denver, Bud and Don approached the AAS Section Chair, Bob Culp, with their proposal. In 1977, Bud Gates, Don Parsons, and Bob Culp organized the first conference, and began the annual series of meetings the following winter. Dan and Lou were delighted to see their concept brought to reality and joined enthusiastically from afar. In March 1978, the First Annual Rocky Mountain Guidance and Control Conference met at Keystone, Colorado. It met there for eighteen years, moving to Breckenridge in 1996 where it has been for the last 20 years. The 2015 Conference was the 38th Annual AAS Rocky Mountain Guidance and Control Conference.

There were thirteen members of the original founders. The first Conference Chair was Bud Gates, the Co-Chair was Section Chair Bob Culp, with the arrangements with Keystone by Don Parsons. The local session chairs were Bob Barsocchi, Carl Henrikson, and Lou Morine. National session chairs were Sherm Seltzer, Pete Kurzhals, Ken Russ, and Lou Herman. The other members of the original organizing committee were Ed Euler, Joe Spencer, and Tom Spencer. Dan DeBra gave the first tutorial.

The style was established at the first Conference, and was adhered to strictly until 2013 involved no parallel sessions, three-hour technical/tutorial sessions at daybreak and late afternoon, and a midday break. For the first fifteen Conferences, the weekend was filled with a tutorial from a distinguished researcher from academia. The Conferences developed a reputation for concentrated, productive work.

After the 2012 conference, it was clear that overall industry budget cuts were leading to reduced attendance and support. In an effort to meet the needs of the constituents, parallel conference sessions were added for 3 of the 8 sessions on a trial basis during the 2013 conference. The success of the parallel sessions was carried forward to 2014 and is expected to continue indefinitely.

A tradition from the beginning and retained until 2014 had been the Conference banquet. It was an elegant feast marked by informality and good cheer. A general interest speaker was a popular feature. The banquet speakers included:

Banquet Speakers

1978	Sherm Seltzer, NASA MSFC, told a joke.
1979	Sherm Seltzer, Control Dynamics, told another joke.
1980	Andrew J. Stofan, NASA Headquarters, "Recent Discoveries through Planetary Exploration."
1981	Jerry Waldvogel, Cornell University, "Mysteries of Animal Navigation."
1982	Robert Crippen, NASA Astronaut, "Flying the Space Shuttle."
1983	James E. Oberg, author, "Sleuthing the Soviet Space Program."
1984	W. J. Boyne, Smithsonian Aerospace Museum, "Preservation of American Aerospace Heritage: A Status on the National Aerospace Museum."
1985	James B. Irwin, NASA Astronaut (retired), "In Search of Noah's Ark."
1986	Roy Garstang, University of Colorado, "Halley's Comet."
1987	Kathryn Sullivan, NASA Astronaut, "Pioneering the Space Frontier."
1988	William E. Kelley and Dan Koblosh, Northrop Aircraft Division, "The Second Best Job in the World, the Filming of Top Gun."
1989	Brig. Gen. Robert Stewart, U.S. Army Strategic Defense Command, "Exploration in Space: A Soldier-Astronaut's Perspective."
1990	Robert Truax, Truax Engineering, "The Good Old Days of Rocketry."
1991	Rear Admiral Thomas Betterton, Space and Naval Warfare Systems Command, "Space Technology: Respond to the Future Maritime Environment."
1992	Jerry Waldvogel, Clemson University, "On Getting There from Here: A Survey of Animal Orientation and Homing."
1993	Nicholas Johnson, Kaman Sciences, "The Soviet Manned Lunar Program."
1994	Steve Saunders, JPL, "Venus: Land of Wind and Fire."
1995	Jeffrey Hoffman, NASA Astronaut, "How We Fixed the Hubble Space Telescope."
1996	William J. O'Neil, Galileo Project Manager, JPL, "PROJECT GALILEO: JUPITER AT LAST! Amazing Journey—Triumphant Arrival."
1997	Robert Legato, Digital Domain, "Animation of Apollo 13."
1998	Jeffrey Harris, Space Imaging, "Information: The Defining Element for Superpowers-Companies & Governments."
1999	Robert Mitchell, Jet Propulsion Laboratories, "Mission to Saturn."
2000	Dr. Richard Zurek, JPL, "Exploring the Climate of Mars: Mars Polar Lander in the Land of the Midnight Sun."
2001	Dr. Donald C. Fraser, Photonics Center, Boston University, "The Future of Light."
2002	Bradford W. Parkinson, Stanford University, "GPS: National Dependence and the Robustness Imperative."
2003	Bill Gregory, Honeywell Corporation, "Mission STS-67, Guidance and Control from an Astronaut's Point of View."
2004	Richard Battin, MIT, "Some Funny Things Happened on the Way to the Moon."
2005	Dr. Matt Golombeck, Senior Scientist, MER Program, JPL, "Mars Science Results from the MER Rovers."
2006	Mary E. Kicza, Deputy Assistant Administrator for Satellite and Information Services, NASA, "NOAA: Observing the Earth from Top to Bottom."

2007 Patrick Moore, Consulting Senior Life Scientist, SAIC and the Navy Marine Mammal Program, "Echolocating Dolphins in the U.S. Navy Marine Mammal Program."

2008 Dr. Ed Hoffman, Director, NASA Academy of Program and Project Leadership, "The Next 50 Years at NASA – Achieving Excellence."

2009 William Pomerantz, Senior Director for Space, The X Prize Foundation, "The Lunar X Prize."

2010 Berrien Moore, Executive Director, Climate Central, "Climate Change and Earth Observations: Challenges and Responsibilities."

2011 Joe Tanner, Former NASA Astronaut, Senior Instructor, University of Colorado, "Building Large Structures in Space."

2012 Greg Chamitoff, NASA Astronaut, "Completing Construction of the International Space Station – The Last Mission of Space Shuttle *Endeavour*."

2013 Thomas J. "Dr. Colorado" Noel, Ph..D., Professor of History and Director of Public History, Preservation & Colorado Studies at University of Colorado Denver, "Welcome to the Highest State: A Quick History of Colorado."

For 2014 a change was made to replace the banquet dinner with a less formal social networking event where conference attendees would have a designated time and venue to encourage building relations. The keynote speaker event of the evening was retained and provided stimulating discussion and entertainment.

2014 Neil Dennehy, Goddard Space Flight Center and Stephen "Phil" Airey, European Space Agency, "Issues Concerning the GN&C Community."

2015 The conference held an extended networking session without a keynote speaker.

In addition to providing for an annual exchange of the most recent advances in research and technology of astronautical guidance and control, for the first fourteen years the Conference featured a full-day tutorial in a specific area of current interest and value to the guidance and control experts attending. The tutor was an academic or researcher of special prominence in the field. These lecturers and their topics were:

Tutorials

1978 Professor Dan DeBra, Stanford University, "Navigation."

1979 Professor William L. Brogan, University of Nebraska, "Kalman Filters Demystified."

1980 Professor J. David Powell, Stanford University, "Digital Control."

1981 Professor Richard H. Battin, Massachusetts Institute of Technology, "Astrodynamics: A New Look at Old Problems."

1982 Professor Robert E. Skelton, Purdue University, "Interactions of Dynamics and Control."

1983 Professor Arthur E. Bryson, Stanford University, "Attitude Stability and Control of Spacecraft."

1984 Dr. William B. Gevarter, NASA Ames, "Artificial Intelligence and Intelligent Robots."

1985 Dr. Nathaniel B. Nichols, The Aerospace Corporation, "Classical Control Theory."

1986 Dr. W. G. Stephenson, Science Applications International Corporation, "Optics in Control Systems."

1987 Professor Dan DeBra, Stanford University, "Guidance and Control: Evolution of Spacecraft Hardware."

1988 Professor Arthur E. Bryson, Stanford University, "Software Application Tools for Modern Controller Development and Analysis."

1989 Professor John L. Junkins, Texas A&M University, "Practical Applications of Modern State Space Analysis in Spacecraft Dynamics, Estimation and Control."

1990 Professor Laurence Young, Massachusetts Institute of Technology, Aerospace Human Factors."

1991 The Low-Earth Orbit Space Environment
Professor G. W. Rosborough, University of Colorado, "Gravity Models."
Professor Ray G. Roble, University of Colorado, "Atmospheric Drag."
Professor Robert D. Culp, University of Colorado, "Orbital Debris."
Dr. James C. Ritter, Naval Research Laboratory, "Radiation."
Dr. Gary Heckman, NOAA, "Magnetics."
Dr. William H. Kinard, NASA Langley, "Atomic Oxygen."

After 1991 there were no more tutorials, but special sessions or featured invited lectures served as focal points for the Conferences. In 1992 the theme was "Mission to Planet Earth" with presentations on all the large Earth Observer programs. In 1993 the feature was "Applications of Modern Control: Hubble Space Telescope Performance Enhancement Study" organized by Angie Bukley of NASA Marshall. In 1994 Jason Speyer of UCLA discussed "Approximate Optimal Guidance for Aerospace Systems." In 1995 a special session on "International Space Programs" featured programs from Canada, Japan, Europe, and South America. In 1996, and again in 1997, one of the most popular features was Professor Juris Vagners, of the University of Washington with "A Control Systems Engineer Examines the Biomechanics of Snow Skiing." In 2005, Angie Bukley chaired a tutorial session "University Work on Precision Pointing and Geolocation." In 2006, a special day for U.S. citizens only was inserted at the beginning of the Conference to allow for topics that were limited due to ITAR constraints. In 2007, two special invited sessions were held: "Lunar Ambitions—The Next Generation" and "Project Orion—The Crew Exploration Vehicle." In 2008, a special panel addressed "G&C Challenges in the Next 50 Years." The 2009 Conference featured a special session on "Constellation Guidance, Navigation, and Control." In 2013, the nail-biting but successful landing of *Curiosity* on Mars inspired a special session on "Entry, Descent and Landing Flight Dynamics."

From the beginning the Conference has provided extensive support for students interested in aerospace guidance and control. The Section, using proceeds from this Conference, annually gives $2,000 in the form of scholarships at the University of Colorado, one to the top Aerospace Engineering Sciences senior, and one to an outstanding Electrical and Computer Engineering senior, who has an interest in aerospace guidance and control. The Section has assured the continuation of these scholarships in perpetuity through an $85,000 endowment. The Section supports other space education through grants to K-12 classes throughout the Section at a rate of over $10,000 per year. All this is made possible by this Conference.

The student scholarship winners attend the Conference as guests of the American Astronautical Society, and are recognized at the banquet where they are presented with scholarship plaques. These scholarship winners have gone on to significant success in the industry.

Scholarship Winners

Academic Year	Aerospace Engr Sciences	Electrical and Computer Engr
1981–1982	Jim Chapel	
1982–1983	Eric Seale	
1983–1984	Doug Stoner	John Mallon
1984–1985	Mike Baldwin	Paul Dassow
1985–1886	Bruce Haines	Steve Piche
1986–1987	Beth Swickard	Mike Clark
1987–1988	Tony Cetuk	Fred Ziel
1988–1989	Mike Mundt	Brian Olson
1989–1990	Keith Wilkins	Jon Lutz
1990–1991	Robert Taylor	Greg Reinacker
1991–1992	Jeff Goss	Mark Ortega
1992–1993	Mike Goodner	Dan Smathers
1993–1994	Mark Baski	George Letey
1994–1995	Chris Jensen	Curt Musfeldt
1995–1996	Mike Jones	Curt Musfeldt
1996–1997	David Son	Kirk Hermann
1997–1998	Tim Rood	Ui Han
1998–1999	Erica Lieb	Kris Reed
1999–2000	Trent Yang	Adam Greengard
2000–2001	Josh Wells	Catherine Allen
2001–2002	Justin Mages	Ryan Avery
2002–2003	Tara Klima	Kiran Murthy
2003–2004	Stephen Russell	Andrew White
2004–2005	Trannon Mosher	Negar Ehsan
2005–2006	Matthew Edwards	Henry Romero
2006–2007	Arseny Dolgov	Henry Romero
2007–2008	Christopher Aiken	Kirk Nichols
2008–2009	Nicholas Hoffmann	Gregory Stahl
2009–2010	Filip Maksimovic	Justin Clark
2010–2011	John Jakes	Filip Maksimovic
2011–2012	Wenceslao Shaw-Cortez	Andrew Thomas
2012–2013	Jacob Haynes	Nicholas Mati
2013–2014	Kirstyn Johnson	Caitlyn Cooke
2014–2015	David Thomas	John Kablubowski

In 2013, in an effort to increase student involvement, a special *Student Paper Session* was added to the program. This session embraces the wealth of research and innovative projects related to spacecraft GN&C being accomplished in the university setting. Papers in this session require a student as the primary author and presenter, and address hardware and software research as well as component, system, or simulation advances. Papers are adjudicated based on level of innovation, applicability and fieldability to near-term systems, clarity of written and verbal delivery, number of completed years of schooling and adherence to delivery schedule.

Student Paper Winners

2013	***1st Place***: Nicholas Truesdale, Kevin Dinkel, Jedediah Diller, Zachary Dischnew, "Daystar: Modeling and Testing a Daytime Star Tracker for High Altitude Balloon Observatories."
	2nd Place: Christopher M. Pong, Kuo-Chia Liu, David W. Miller, "Angular Rate Estimation from Geomagnetic Field Measurements and Observability Singularity Avoidance during Detumbling and Sun Acquisition."
	3rd Place: Gregory Eslinger, "Electromagnetic Formation Flight Control Using Dynamic Programming."
2014	***1st Place***: Dylan Conway, Brent Macomber, Kurt A. Cavalieri, John L. Junkins, "Vision-Based Relative Navigation Filter for Asteroid Rendezvous."
	2nd Place: Robyn M. Woollands, John L. Junkins, "A New Solution for the General Lambert Problem."
	3rd Place: Alex Perez, "Closed-Loop GN&C Linear Covariance Analysis for Mission Safety."
2015	***1st Place***: Andrew Liounis, Alexander Entrekin, Josh Gerhard, John Christian, "Performance Assessment of Horizon-Based Optical Navigation Techniques."
	2nd Place: J. Micah Fry, "Aerodynamic Passive Attitude Control: A New Approach to Attitude Propagation and a Nano-satellite Application."
	3rd Place: Siamak Hesar, Jeffrey S. Parker, Jay McMahon, George H. Born, "Small Body Gravity Field Estimation Using Liaison Supplemented Optical Navigation."

In 2015 the AAS Rocky Mountain Section partnered with the University of Colorado and hosted the inaugural STEM SCAPE conference on Saturday, which provided an introduction for the students to working in a STEM field and motivated them to pursue professional careers in aerospace engineering. This highly successful session brought in 98 high school students, 20 college students and included a design project, panel discussions, an opportunity to meet industry representatives, practice interviews for the college students and a keynote speech.

The Rocky Mountain Section of the American Astronautical Society established the Rocky Mountain Guidance and Control Committee, chaired *ex-officio* by the next Conference Chair, to prepare and run the annual Conference. The Conference, now named the AAS Guidance, Navigation and Control Conference, and sponsored by the national AAS, annually attracts about 200 of the nation's top specialists in space guidance and control.

	Conference Chair	**Attendance**
1978	Robert L. Gates	83
1979	Robert D. Culp	109
1980	Louis L. Morine	130
1981	Carl Henrikson	150

1982	W. Edwin Dorroh, Jr.	180
1983	Zubin Emsley	192
1984	Parker S. Stafford	203
1985	Charles A. Cullian	200
1986	John C. Durrett	186
1987	Terry Kelly	201
1988	Paul Shattuck	244
1989	Robert A. Lewis	201
1990	Arlo Gravseth	254
1991	James McQuerry	256
1992	Dick Zietz	258
1993	George Bickley	220
1994	Ron Rausch	182
1995	Jim Medbery	169
1996	Marv Odefey	186
1997	Stuart Wiens	192
1998	David Igli	189
1999	Doug Wiemer	188
2000	Eileen Dukes	199
2001	Charlie Schira	189
2002	Steve Jolly	151
2003	Ian Gravseth	178
2004	Jim Chapel	137
2005	Bill Frazier	140
2006	Steve Jolly	182
2007	Heidi Hallowell	206
2008	Michael Drews	189
2009	Ed Friedman	160
2010	Shawn McQuerry	189
2011	Kyle Miller	161
2012	Michael Osborne	140
2013	Lisa Hardaway	181
2014	Alexander May	180
2015	Ian Gravseth	195

The AAS Guidance and Control Technical Committee, with its national representation, provides oversight to the local conference committee. W. Edwin Dorroh, Jr., was the first chairman of the AAS Guidance and Control Committee; from 1985 through 1995 Bud Gates chaired the committee; from 1995 through 2000, James McQuerry chaired the committee. From 2000 through 2007, Larry Germann chaired this committee, and James McQuerry has chaired the committee since. The committee meets every year at the Conference, and also sometimes at the summer Guidance and Control Meeting, or at the fall AAS Annual Meeting.

The AAS Guidance and Control Conference, hosted by the Rocky Mountain Section in Colorado, continues as the premier conference of its type. As a National Conference sponsored by the AAS, it promises to be the preferred idea exchange for guidance and control experts for years to come.

On behalf of the Conference Committee and the Section,

Dr. Ian J. Gravseth
Ball Aerospace & Technologies Corp.
Boulder, Colorado

PREFACE

This year marked the 38th anniversary of the AAS Rocky Mountain Section's Guidance and Control Conference. It was held in Breckenridge, Colorado at the Beaver Run Resort from January 30 – February 5, 2015. The planning committee and the national chairs did an outstanding job in creating a highly-technical conference experience, and I extend many thanks to all those involved.

The conference began this year on Friday morning with a pair of classified sessions hosted at Ball Aerospace's facility in the Denver Metro area. This offered a unique opportunity to share and network at a level usually unavailable to many in our GN&C community. The two sessions were titled *Classified Sessions on Advances in G&C and Recent Experiences*.

The traditional five day conference format officially began on Saturday morning with an impressive *Student Innovations in GN&C* session featuring a student competition with scholarship prizes. Following the student paper session, the conference hosted the inaugural STEM-SCAPE event, which introduced nearly 100 area high school students to careers in an aerospace engineering field.

To cap off the day, the *Technical Exhibits* session was held Saturday afternoon. Twenty companies and organizations participated with many hardware demonstrations as well as excellent technical interchanges between conferees, vendors, and family. The session was accompanied by a buffet dinner. Many family members and children were present, greatly enhancing the collegiality of the session. The highly-experienced technical exhibits team did an outstanding job organizing the vendors and exhibits.

Other sessions during the conference examined the current state-of-the-art in GN&C and other focus areas that are of interest to the GN&C community. *The Roadmaps and Future Mission Concepts* session was presented on Sunday morning, and a *Space Debris* session was held on Sunday afternoon. Monday morning two concurrent sessions, *In Space Propulsion Innovations* and *Advances in GN&C Hardware* were held. Monday evening presented the *Recent Experiences I* session, and an additional session on *Low-Thrust Mission Planning*. The traditional banquet on Monday evening was revamped to offer better networking opportunities.

Tuesday morning's parallel sessions included *Advances in GN&C Software*, and *Proximity Operations,* which concentrated on proximity operations around man-made objects. Tuesday evening held another proximity operations session, which focused on *Small Body Proximity Operations* near asteroids and comets.

We were fortunate to have astronaut Joe Tanner give an exciting presentation to the children visiting with us at the conference. And also, we had a daily *Poster Session* where posters were on display so attendees could speak one-on-one with the authors during breakfast and break periods.

Finally, Wednesday morning featured the popular closing session *Recent Experiences II*. This traditional session contained candid first-hand accounts of successes and failures for missions, which contain valuable lessons for the GN&C community.

The participation and support of our many colleagues in the industry helped make the 38th Annual Rocky Mountain AAS G&C conference a great success. The technical committee, session chairs, and national chairs were unfailingly supportive and fully committed to the technical success of the conference. Special thanks also goes to Carolyn O'Brien of Lockheed Martin, Lis Garratt of Ball Aerospace, and the staff at Beaver Run for their professionalism and attention to the operational details that made this conference happen!

Dr. Ian J. Gravseth
Conference Chairperson
2015 AAS Guidance, Navigation
and Control Conference

CONTENTS

STUDENT INNOVATIONS IN GUIDANCE, NAVIGATION AND CONTROL

SESSION I

This session embraced the wealth of research and innovative projects related to spacecraft GN&C being accomplished in the university setting. Papers in this session addressed hardware/software research as well as component, system or simulation advances. Papers submitted were required to have a student as the primary author and presenter. Papers were adjudicated based on level of innovation, complexity of problem solved, perceived technical readiness level, applicability and fieldability to near-term systems, clarity of written and verbal delivery, number of completed years of schooling and adherence to delivery schedule. Prizes were awarded to the top 3 papers sponsored by: Space X, Blue Canyon Technologies and Intuitive Machines, LLC.

National Chairpersons:

Tim Crain
Intuitive Machines

David Geller
Utah State University

Local Chairpersons:

Dave Chart
Lockheed Martin Space Systems Company

Jeff Bladt
Ball Aerospace & Technologies Corp.

The following paper was not available for publication:

AAS 15-026
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 15-029 to -030

AAS 15-021

ATTITUDE CONTROL SYSTEM DESIGN FOR MULTI-MODE PROXIMITY OPERATIONS AND IMAGING WITH A 6U CUBESAT

Francisco J. Franquiz,[*] Bogdan Udrea,[†]
Luis A. Sánchez[‡] and Shane T. Stebler[§]

The work presented in this paper focuses on the design and analysis of an attitude determination and control subsystem (ADCS) for a proximity operation and imaging mission carried out by a 6U CubeSat class nano-satellite. The satellite is equipped with a custom cold gas propulsion system which provides the capability for both orbital maneuvering and reaction attitude control using eight pairs of miniaturized thrusters. Mission imaging requirements flow down to a pointing control accuracy of 1 arcmin at 3s in the direction of the target resident space object (RSO). The attitude control system utilizes two control laws to achieve the pointing control requirement. The first control law employs eigenaxis maneuvering and is used for large angle slews, while the second law implements PID controllers about each axis for accurate pointing during imaging. An autonomous switching algorithm manages the transitions between control laws based on operational modes and uses the payload cameras as sensors in the loop to prevent loss of accuracy.

This paper discusses a trade study between an actuator comprised solely of reaction control system (RCS) thrusters and a traditional reaction wheel system, which uses the same RCS for wheel momentum off-loading. This trade study addresses the effects of these two actuators on pointing accuracy, electrical energy, and propellant consumption. Additionally, an extended Kalman filter and a gyro-less angular rate observer are implemented to study their influence on performance. The ADCS capabilities are showcased within an extensive mission operation model focused on separate subsystem performance and integration. Results are presented for numerical simulations of a circular relative orbit with a 250 m radius about an RSO at a 500 km altitude and 29° inclination. It is shown that mission requirements are satisfied during slew maneuvers, object tracking, and while centering the RSO in the payload camera frame. The simulation shows that the spacecraft pointing progresses seamlessly between modes and a detailed accounting of actuator and sensor performance is presented. Progress in implementing and testing the algorithms in a real-time testbed, that will lead to hardware-in-the-loop simulations, is also described. [View Full Paper]

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AERODYNAMIC PASSIVE ATTITUDE CONTROL: ATTITUDE PROPAGATION AND A NANO-SATELLITE APPLICATION

J. Micah Fry*

Aerodynamic passive attitude control is discussed and proposed for the soon-to-launch GASPACS (Get Away Special Passive Attitude Control Satellite) CubeSat. A component approach to modeling aerodynamic torque for attitude propagation is applied to GASPACS' three stages of flight. Magnetic hysteresis material is considered as a rotational damping mechanism and simulation results demonstrate the dynamic effects of using magnetic hysteresis material. With a developed aerodynamic design and hysteresis rods, it is concluded that GASPACS will passively stabilize to within 25° of its velocity vector at a rotational rate of ±[1.5, 0.25, 0.25] °/s by 24 hours of flight. This demonstrates that the open source attitude propagation code is qualified, easily modifiable, and capable in optimizing passive attitude control systems. [View Full Paper]

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AAS 15-023

PERFORMANCE ASSESSMENT OF HORIZON-BASED OPTICAL NAVIGATION TECHNIQUES

Andrew J. Liounis,[*] Joshua Gerhard[*] and John Christian[†]

Exploration beyond low Earth orbit continues to be a key goal for many space programs today. For these missions it is becoming increasingly necessary to utilize optical techniques for navigation. While a variety of optical navigation (OPNAV) measurement types are available, the centroid and apparent diameter method is an interesting technique that has received considerable attention in recent years by various authors. Prior work, however, has mostly focused on state estimation, with only limited consideration given to the estimate covariance. The present paper addresses this knowledge gap by providing a detailed treatment of the error sources that influence the quality of a centroid and apparent diameter OPNAV measurement. The work begins with a careful examination of potential image processing algorithms for autonomously extracting points along the Moon's (or Earth's) limb in an image. These algorithms are assessed for both their robustness to various illumination conditions and the noise/bias of the estimated limb locations. With the statistics of the limb finding processes in hand, attention is turned to understanding how errors inherent in image formation and processing propagate through the projective geometry and nonlinear estimation routines used to compute the spacecraft position. The theories developed here are validated by processing both simulated and real images, and results are shown. [View Full Paper]

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AAS 15-024

SMALL BODY GRAVITY FIELD ESTIMATION USING LIAISON SUPPLEMENTED OPTICAL NAVIGATION

Siamak G. Hesar,[*] Jeffrey S. Parker,[†] Jay McMahon[‡] and George H. Born[§]

This paper presents a new navigation technique for estimating the gravity field of a small body. The proposed technique takes advantage of autonomous onboard optical navigation supplemented with in-situ satellite-to-satellite radiometric measurements. Simulated in-situ relative radiometric measurements are generated between a navigation satellite and a radio beacon orbiting the asteroid 433 Eros. In general, relative observations alone are not sufficient to provide a unique orbit determination solution. However, taking advantage of the asymmetric gravity field of an asteroid by solving for its gravity field, relative measurements can converge on a unique solution. Results from a covariance study showed that the proposed navigation technique is capable of estimating the position of the navigation satellite with sub-meter level precision and recover the gravity field of the asteroid up to degree 9 of the spherical harmonics expansion.
[View Full Paper]

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§ Director Emeritus, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado 80309, U.S.A.

AAS 15-025

HARDWARE-IN-THE-LOOP VALIDATION OF SENSING AND ALGORITHMS FOR AUTONOMOUS DESCENT AND LANDING

Austin B. Probe,[*] Dylan Conway,[*] Brent Macomber,[*] Clark Moody[*] and John L. Junkins[†]

The current state of the practice for autonomous descent and landing consists of pre-orchestrated trajectories touching down within a pre-selected landing ellipse, as demonstrated with the Mars Science Laboratory, the Rosetta Philae Lander, and the planned OSIRIS-REx mission. Future missions designed with more specific scientific objectives or with the aim of in-situ resource extraction will require significantly more precise autonomous descent and landing capabilities. The Texas A&M Land, Air, and Space Robotics Lab (LASR) has developed a candidate system to provide real time autonomous Guidance, Navigation, and Control (GN&C) during descent and landing based on computational vision. As ground based intervention is impossible during landing situations, any potential method must be extensively tested and validated prior to flight. This paper describes a hardware-in-the-loop implementation of the candidate landing and navigation system in a characteristic small body landing scenario using the Holonomic Omnidirectional Motion Emulation Robot (HOMER) as a simulation platform. A detailed description of the landing GN&C system and the experimental test case is provided, along with results for the performance of each system compared to "truth" data from laboratory sensing systems. [View Full Paper]

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EXPERIMENTAL VALIDATION OF AN INERTIA-FREE CONTROLLER AND A MULTIPLICATIVE EKF FOR POSE TRACKING AND ESTIMATION BASED ON DUAL QUATERNIONS

Alfredo Valverde,[*] Nuno Filipe,[†] Michail Kontitsis[‡] and Panagiotis Tsiotras[§]

This paper presents the experimental results from the validation of a dual quaternion inertia-free adaptive controller, in combination with a continuous/discrete Dual Quaternion-Multiplicative Extended Kalman Filter (DQ-MEKF) for spacecraft pose estimation and tracking. The experiments were conducted on the Autonomous Spacecraft Testing of Robotic Operations in Space (ASTROS) facility, an experimental 5-DOF platform located at the Georgia Institute of Technology, equipped with rate gyros, inertial measurement unit, reaction wheels, cameras, and cold-gas thrusters. Experimental results are given for a maneuver in closed-loop, and are evaluated using a VICON optical tracking system. [View Full Paper]

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ANALYSIS OF ASTRODYNAMIC STATE VARIABLE FORMULATIONS

Chris Shelton* **and Ryan Weisman†**

The orbit of a satellite is usually characterized by position and velocity vectors or by a set of state variables called orbital elements. While the coordinates used to model the system do not change its dynamics, they can induce singularities limiting the orbital motion they can describe. This is especially problematic when generating an optimal trajectory between two points where any type of orbit is allowed. Other formulations can be computationally expensive. As a result, many state variable formulations exist. In this paper, a comparative study is sought to deduce the computational advantages and accuracy of several different state variable formulations, including Cartesian coordinates, classical orbital elements, equinoctial elements and Dromo elements. Accuracy and computational performance will be presented as a function of different orbit types and orbital perturbations. The results of this study will then be used to aid in trajectory optimization and uncertainty propagation studies. [View Full Paper]

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ROADMAPS AND FUTURE MISSION CONCEPTS

SESSION III

As part of their individual strategic planning efforts NASA, DoD, ESA and other worldwide civilian and national defense space agencies have created, or are in the process of creating roadmaps, for both their advanced GN&C technologies and for their future payload (e.g. sensors and instruments), missions and systems. These international civilian and military space agencies are devoting energy to systematically and strategically plan their GN&C technology also performing studies and analyses to assess their future system objectives, from both the perspectives of technological readiness and programmatic feasibility, as part of the process of formulating ambitious future mission concepts. While many of these future mission concepts are notional it is clear that several will require significant innovation and the first-time infusion of emerging technologies to satisfy challenging GN&C system engineering requirements. In this session the authors presented papers on GN&C technology roadmaps, future mission concepts and their inter-relationship.

National Chairpersons:

Cornelius J. Dennehy
NASA Engineering & Safety Center (NESC)

Davin K. Swanson
The Aerospace Corporation

Richard Scott Erwin
Air Force Research Laboratory, Space Vehicles Directorate

Local Chairperson:

Scott Mitchell
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The following paper was not available for publication:

AAS 15-044
Not Available (Withdrawn)

The following paper numbers were not assigned:

AAS 15-049 and -050

AAS 15-041

APNM SPACECRAFT: AN EP-BASED VERSATILE MISSION CONCEPT WITH A SINGLE INTEGRATED GNC SOLUTION FOR ACTIVE MULTI-DEBRIS REMOVAL AND SATELLITE COMMERCIAL SERVICING

Guillaume Pionnier* and Pierre-Nicolas Gineste†

Airbus Defence and Space believes – also highlighted in the roadmaps of the major space agencies – that many significant GNC improvements need to be made in order to face the very challenging upcoming missions in the next two decades, such as Active Debris Removal, Commercial Servicing (and Interplanetary missions). This paper describes the studies self-conducted by AIRBUS DS on the preliminary design of a versatile and modular spacecraft, with a specific focus on the single integrated GNC solution for Electrical Propulsion-based (EP-based) transfer phases and mixed Electrical and Chemical Propulsion-based non-cooperative rendezvous. Key characteristics of the vehicle, as well as the main GNC features to be implemented are also reviewed.

[View Full Paper]

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LOOKING BACK AND LOOKING FORWARD: REPRISING THE PROMISE AND PREDICTING THE FUTURE OF FORMATION FLYING AND SPACEBORNE GPS NAVIGATION SYSTEMS

Frank H. Bauer* and Neil Dennehy†

A retrospective consideration of two 15-year old Guidance, Navigation and Control (GN&C) technology 'vision' predictions will be the focus of this paper. A look back analysis and critique of these late 1990s technology roadmaps outlining the future vision, for two then nascent, but rapidly emerging, GN&C technologies will be performed. Specifically, these two GN&C technologies were: 1) multi-spacecraft formation flying and 2) the spaceborne use and exploitation of global positioning system (GPS) signals to enable formation flying.

This paper reprises the promise of formation flying and spaceborne GPS as depicted in the cited 19991 and 19982 papers. It will discuss what happened to cause that promise to be unfulfilled and the reasons why the envisioned formation flying dream has yet to become a reality. The recent technology trends over the past few years will then be identified and a renewed government interest in spacecraft formation flying/cluster flight will be highlighted. The authors will conclude with a reality-tempered perspective, 15 years after the initial technology roadmaps were published, predicting a promising future of spacecraft formation flying technology development over the next decade. [View Full Paper]

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AAS 15-043

INDUSTRY PERSPECTIVE ON SPACE UNIVERSAL MODULAR ARCHITECTURE (SUMO) CONCEPTS APPLIED TO MOMENTUM CONTROL COMPONENTS

Ted Bonk,* Tim Hindle† and Tim Hintz†

There is currently significant interest in reducing the cost of satellites by leveraging existing and evolving standards with respect to spacecraft component data and electrical interfaces. The Space Universal Modular Architecture (SUMO) initiative has reached out to industry to generate support of the development and implementation of such standards for spacecraft components. This paper discusses this topic, and how these concepts apply to momentum control components at Honeywell. Specifically, Reaction Wheel Assemblies (RWAs) and Control Moment Gyroscopes (CMGs) are discussed with respect to standardization of interfaces, including some perspective for past and current products. More recently, Honeywell has developed Momentum Control Assemblies (MCAs) for select missions, and will provide some insight into the addition benefits this approach provides, including a discussion of the current types of interfaces utilized. Finally, a discussion of the current progression towards Momentum Control Systems (MCSs) will be described, which further simplifies both the electrical/data interface as well as the mechanical interface for future missions. [View Full Paper]

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A MINIATURE, LOW-POWER STAR TRACKER FOR PRECISION POINTING NANOSATELLITES*

Darren W. Rowen,† Alexander C. Utter,‡ Richard M. Dolphus§ and Eddson M. Alcid**

The design of a compact, low-power star-tracker system is presented for attitude determination in nanosatellites where size, weight, and power are at an extreme premium. The system contains up to five CMOS camera modules linked to a shared image-processing board. Frame capture is handled by a Field-Programmable Gate Array (FPGA), which applies a series of filters to mitigate image-sensor artifacts and automatically adjust luminance thresholds. Filtered pixel data is transferred to a low-power PIC microprocessor, which matches the image against a catalog of stars to solve for attitude. This division of processing minimizes the required memory footprint and maximizes the idle time of power-intensive circuits for improved energy efficiency. PIC memory usage is kept within limits by using only a subset of the star catalog based on partitioning of the full catalog into regions that are loaded into memory as needed. The attitude determination algorithm finds the solution that maximizes the number of pixel cluster locations matched to star catalog locations, with the secondary objective of minimizing line of sight residuals; this approach is tolerant to the presence of hot pixels and non-star objects in the image. An attitude quaternion (as well as the measurement geometry matrix) is provided for use in a recursive attitude determination filter (e.g., to blend with gyro data). Test results are presented showing sensitivity as a function of exposure time.
[View Full Paper]

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AAS 15-046

NASA'S SPACE NAVIGATION ROADMAPS

James S. Schier*

In 2012, the National Research Council's document "NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space" identified a number of navigation technology developments. High priority navigation technologies required to support anticipated future missions included: 1. Onboard Autonomous Navigation and Maneuvering (OANM); and 2. Timekeeping and Time Distribution. Top technical challenges included "Autonomous and Accurate Navigation" for both absolute and relative navigation enabling autonomous rendezvous and docking as well as precision entry, descent, and landing.

In 2014, NASA updated this analysis by defining specific Design Reference Missions (DRM) through 2040 for science, exploration, and aeronautics and evaluating the capabilities needed to enable or enhance each of these DRMs. The Space Communications and Navigation Program is refining its technology investments and long range architecture plans based on this update. This paper will present the results of investment decisions being made now and preliminary results of architecture studies currently in progress that will define future space Position, Navigation, and Timing (PNT) capabilities. This will include advances in optical tracking, hybrid RF/optical systems, atomic clocks, and Global Positioning System. [View Full Paper]

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AAS 15-047

AGILITOID-BASED DESIGN ANALYSIS OF NEXT GENERATION ATTITUDE CONTROL SYSTEMS

Mark Karpenko,[*] Jeffery T. King[†] and I. Michael Ross[‡]

The agility of a rigid body spacecraft can be expressed in terms of a geometric, three-dimensional solid called the agilitoid. Originally developed as a means for explaining the concept of "hidden agility" made visible through the use of optimal control techniques, a modified agilitoid is presented here that is compatible with the conventional eigenaxis maneuver. Parameters of the James Webb Space Telescope are used to demonstrate how the modified agilitoid can be applied to quickly and accurately size attitude control systems for future missions. The new concept is also used to show how a reaction wheel array can be configured to reduce the mass budget in the design of future spacecraft. No modification of flight software is necessary to use the new approach. Only a simple change in the parameters of the maneuver generating logic is needed. [View Full Paper]

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ONBOARD GUIDANCE, NAVIGATION, AND CONTROL TECHNOLOGY ASSESSMENT FOR FUTURE PLANETARY SCIENCE MISSIONS

Joseph E. Riedel and MiMi Aung*

This paper presents an evaluation of the onboard GN&C capabilities and technologies needed for future missions pursuing NASA's planetary science goals. In particular, this assessment covers attitude estimation and control in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics are strongly coupled or performed primarily onboard (as is the case during certain critical phases, such as entry, descent, and landing, in some planetary missions). This work first surveys the technologies, appraises their applicability to future NASA planetary missions, and then quantitatively assesses priorities for NASA based on likely need, relevance and optionally cost. [View Full Paper]

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SPACE DEBRIS

SESSION IV

Although many methods of monitoring and detecting debris for avoidance purposes are already in place, space debris continues to be a growing issue within the aerospace community. This session focused on characterization of the current debris environment and also discussed ongoing or future efforts for debris mitigation that may be underway or are proposed.

National Chairpersons:

Gene Stansbery
NASA Orbital Debris
Program Office

Tim Coffin, Brigadier General,
United States Army,
Commander, White Sands
Missile Range

Local Chairpersons:

Cheryl Walker
Lockheed Martin
Space Systems Company

Steve Jolly
Lockheed Martin
Space Systems Company

John Abrams
Analytical Mechanics Associates,
Inc.

The following paper was not available for publication:

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The following paper numbers were not assigned:

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AAS 15-051

APPLICATION OF LOW-THRUST TRAJECTORY ANALYSIS TO SOLAR ELECTRIC PROPULSION (SEP) ORBITAL DEBRIS REMOVAL FERRY MISSION CONCEPT

Matthew E. Duchek*

Active debris removal (ADR) mission concepts that utilize a solar electric propulsion (SEP) spacecraft bus to rendezvous with and deorbit multiple objects have been proposed in various forms. These concepts have used low-thrust delta-V approximations to estimate the amount of fuel needed for the mission profile. These approximations, based on separate maneuvers for altitude raising, plane changing, etc. are useful for initial sizing, but are conservative and do not account for many of the trade-offs in trajectory design, including real target ephemeris, target order, loiter at low or high altitudes, right ascension of the ascending node (RAAN) drift, etc. This paper analyzes trajectory options with a low-thrust propagator for a group of representative ADR targets. A more complete picture of the trajectory required for an ADR mission is presented that provides insight into the techniques that can be used to make a multi-target mission more efficient. Results related to target selection for an efficient trajectory are discussed. Referencing previous research by the authors, the effects of the trajectory analysis on sizing of a demonstration mission concept are examined. [View Full Paper]

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FALCO: AN AFFORDABLE ORBITAL DEBRIS REMOVAL MISSION SIMPLIFIED BY USE OF A PASSIVE DESPIN DEVICE

Reuben R. Rohrschneider,* Robert Arentz,† Ian Gravseth,‡ Brett Landin,‡ Larry Guy,‡ Rusty Schweickart‡ and Scott Mitchell§

The Falco orbital debris removal mission is a concept devised to provide a credible solution to removing a large piece of orbital debris from space for a reasonable mission cost. The target orbital debris for the mission is the defunct Infrared Astronomical Satellite (IRAS) telescope, which was chosen because it won't deorbit on its own, and because Ball Aerospace built it and so knows the details of the vehicle. The overall mission concept is very straightforward, except for the passive despin device that is used to simplify capture of the spinning spacecraft. The passive despin device is a novel method of reducing the spin rate of the orbital debris using the Earth's magnetic field, and helps to simplify the guidance, navigation, and control aspects of capturing a spinning piece of orbital debris. This paper will provide an overview of the mission, with a focus on the passive despin device and the simplifications it provides to the overall system. [View Full Paper]

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PERFORMANCE OPTIMIZATION STUDY FOR TOUCHLESS ELECTROSTATIC SPACECRAFT DE-SPIN OPERATIONS

Daan Stevenson* and Hanspeter Schaub†

An electrostatic de-spin concept has been proposed for remotely removing excess rotation rates from uncontrolled satellites in the GEO orbit regime. While the 1D-dynamics and control of this system have already been analyzed extensively, a study is herein conducted to determine how to optimize the performance of the system for future mission design. First, two different methods for simulating the baseline Coulomb de-spin system are presented. Then, the sensitivity of de-spin time, required thrust profiles, and system displacement to variations in spacecraft sizes, shapes, and separation distance is considered. The findings show that increasing the size of the servicing craft results in diminishing returns in performance, and that the optimal aspect ratio of the targeted debris satellite is quite low, assuming constant density. Furthermore, various position and attitude control schemes for the servicing craft are studied to see if the de-spin time can be reduced. Performance is improved considerably by varying the relative position to maintain a minimum surface to surface distance or by circumnavigating the debris to operate with maximum control torques, but both approaches significantly increase the required thrust magnitudes and fuel expenditure. Another promising approach is one where the servicing craft adjusts its attitude to position multiple voltage controlled features so that they impart optimal arresting torques on the spinning debris object. [View Full Paper]

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AAS 15-055

A RENDEZVOUS AND DOCKING MISSION TARGET SATELLITE WITH UNUSUAL REQUIREMENTS

Anja Nicolai,[*] Christian Raschke,[†] Stephan Stoltz[‡] and Robert Eberwein[†]

During this Phase-B study, a satellite was designed which will serve as a target / client for a rendezvous and docking technology demonstration mission. During the mission, several approaches, rendezvous, berthing and docking maneuvers by the servicing satellite are planned. To demonstrate the full capability of the approach technology, the target satellite shall simulate a cooperating as well as a non cooperating target. Therefore uncommon attitude control system (ACS) modes were required, ranging from different cooperative 3-axis controlled inertial pointing modes to a 4°/s spinning mode and a 4°/s tumbling mode with a 10° nutation angle. The paper will give a brief overview over the client satellite and the driving design requirements and challenges. Then it will describe the attitude control system in detail and present simulation results for the different ACS modes. [View Full Paper]

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IN SPACE
PROPULSION INNOVATIONS

SESSION V

Technology innovations in the area of space propulsion have become prominent recently with notable DOD, NASA, and industry investment in green propellant thrusters, cryogenic propellant storage, high-power electric propulsion systems, and propellantless propulsion. Additionally, trends toward employing small spacecraft for an increasing range of applications are driving demand for efficient propulsion technologies for high-mobility micro/nano/picosatellites. This session highlighted emerging propulsion hardware and systems and their GN&C implications that address diverse implementations such as fine pointing for science spacecraft, low-thrust cargo transfer, high-thrust Earth and Mars departure, and descent to / ascent from planetary bodies.

National Chairpersons:

Jeffrey Sheehy
NASA Space Technology
Mission Directorate (STMD)

Roger Myers
Aerojet Rocketdyne

Local Chairpersons:

Bryce Unruh
Ball Aerospace & Technologies
Corp.

Christy Edwards-Stewart
Lockheed Martin
Space Systems Company

The following paper numbers were not assigned:

AAS 15-069 to -070

NEW DEVELOPMENTS IN CONVENTIONAL PROPULSION[*]

Olwen M. Morgan,[†] Roger Myers[‡] and Fred C. Wilson[§]

There have been both evolutionary and revolutionary developments in spacecraft propulsion over the years. Evolutionary developments in chemical propulsion have been enabled by modern materials, machining methods and joining techniques. Revolutionary developments in electric propulsion have been enabled by higher power solar panels and vastly improved electronics. Evolutionary improvements have also resulted from modern materials, machining methods and joining techniques. This paper will present some specific examples of both evolutionary and revolutionary developments and link them with the "push" (expanded capabilities) and the "pull" (expanded requirements) that enabled the change. Recommendations for future work will be included.
[View Full Paper]

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* Aerojet Rocketdyne Approval No. 2015-007.

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THE AIR FORCE RESEARCH LABORATORY'S IN-SPACE PROPULSION PROGRAM*

Brian E. Beal†

The Air Force Research Laboratory's In-Space Propulsion Branch (AFRL / RQRS) has primary responsibility for development and maturation of spacecraft propulsion technologies in support of future Air Force missions. AFRL has active research programs in both advanced chemical propulsion and electric propulsion. Advanced chemical propulsion programs are developing thrusters that operate on a class of non-toxic, energetic propellants that offer performance surpassing that of state-of-the-art hydrazine systems. AFRL's electric propulsion efforts are focused on sustainment of Hall effect thruster technology and development of higher-performing, lower-mass alternatives such as electrosprays and field reverse configuration thrusters. Fundamental relations showing the influence of key technology metrics such as mass and specific impulse on mission-level performance are presented to illustrate the rationale behind AFRL's technology development strategy. [View Full Paper]

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* Distribution A: Approved for Public Release; Distribution Unlimited. (PA Case File: 15047).

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AAS 15-063

GREEN PROPELLANT INFUSION MISSION PROGRAM OVERVIEW, FLIGHT OPERATIONS, AND ADCS DEVELOPMENT

Chris McLean and Brian Marotta*

The NASA Space Technology mission Directorate's (STMD) Green Propellant Infusion Mission (GPIM) Technology Demonstration Mission (TDM) will provide a flight demonstration of an AF-M315E green propellant propulsion system. The propulsion subsystem that was developed under this project includes both 1 N and 22 N thrusters. Development ground testing of these thrusters included impulse bit and thruster performance characterization over a broad range of thruster pulse width and inlet pressure operating conditions. The flight subsystem is integrated as a dedicated payload attached to the Payload Interface Plate (PIP) on a Ball BCP-100 spacecraft. Program goals required specific on-orbit characterization of the spacecraft's propulsion capabilities, including 3-axis control, pointing accuracy evaluation, and momentum dumping employing four 1 N thrusters. On-orbit measurement of the 1 N thruster Ibit will be performed to evaluate the performance of these thrusters over their operational life. Orbit lowering and plane change operations of the GPIM spacecraft are performed during divert, or 'delta-V' operation, pulse width modulating the four 1 N thrusters to provide thrust vector control of the spacecraft while the single 22 N thruster is firing.

The addition of thruster control algorithms and flight modes to baseline BCP-100 flight software was required to meet program objectives. Making use of Ball heritage flight software, the following capabilities were added; changing orbit parameters via delta-V mode, 3-axis attitude control on thrusters, reaction wheel momentum management, open-loop burns for performing orbit trim burns and thruster characterization, and thruster based detumble to null undesired body rates. Performance testing of the 1 N thrusters will consist of executing a set series of short pulses on each thruster and using star tracker data to determine the amount of force each pulse imparted onto the spacecraft. [View Full Paper]

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AAS 15-064

ADVANCES IN PROPELLANTLESS IN-SPACE PROPULSION TECHNOLOGIES

Les Johnson*

In order to implement the next generation of robotic space missions affordably and with reasonable flight times, improvements in in-space propulsion must be achieved. For robotic exploration and science missions, increased efficiencies of future propulsion systems are critical to reduce overall life-cycle costs. Some future missions being proposed, including outer solar system rendezvous and sample return missions, will require 2 to 3 times more total change in velocity over their mission lives than can be achieved with chemical rockets or electric propulsion systems. Some of the most promising technologies for enabling these ambitious missions use the environment of space itself for energy and propulsion and are generically called, "propellantless" because they do not require onboard fuel to achieve thrust. An overview of the state-of-the-art propellantless propulsion technologies such as solar sails, electric sails, and electrodynamic tethers will be provided. [View Full Paper]

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SYSTEM IMPLICATIONS FOR GN&C AND HIGH POWER SEP SPACECRAFT

Steven Overton,[*] Joe Cassady,[†] Kevin Kelleher[‡] and Martha Kendall[§]

High power solar electric propulsion (SEP) spacecraft presents new challenges and demands for the GN&C subsystem. Available and emerging state of the art propulsion technologies present GN&C engineers with a wide variety of options that offer wide-ranging capabilities, implications, and benefits for SEP vehicles. Propulsion technologies – ranging from high-thrust, relatively low Isp (~235 secretary) monopropellant thrusters to very-low thrust electric propulsion devices delivering up to several thousand (<1800 to >6000) seconds Isp – span a spectrum of varying system launch mass vs. required power, complexity, and mission duration. System and subsystem trades are required to determine an optimum propulsion technology, or combination of technologies, for a given mission that will provide the best balance of cost vs. mission objectives and assurance. Specifically, with the current trend towards higher power spacecraft utilizing SEP, GN&C engineers should consider investigating and developing new algorithms and tools to maximize the payoffs. This paper provides a comprehensive classification of propulsion options currently available to the GN&C community according to critical characteristics for various SEP mission classes and ConOps. These options will include high-TRL electric propulsion options, e.g. arcjet, Hall thruster, and ion thruster technologies, in possible combination with traditional monopropellant and bipropellant thrusters where necessary and appropriate. Each of these technologies has unique benefits and niche areas that they excel in depending on the ConOps. These SOA and emerging propulsion technologies enable new mission capabilities that need to be understood and traded in order to realize their full potential and payoff. [View Full Paper]

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AAS 15-066

GUIDANCE, NAVIGATION, AND CONTROL CONSIDERATIONS FOR NUCLEAR THERMAL PROPULSION

Michael G. Houts,[*] Doyce P. Mitchell[†] and Tony Kim[‡]

The fundamental capability of Nuclear Thermal Propulsion (NTP) is game changing for space exploration. A first generation NTP system could provide high thrust at a specific impulse above 900 s, roughly double that of state of the art chemical engines. Characteristics of fission and NTP indicate that useful first generation systems will provide a foundation for future systems with extremely high performance. The role of a first generation NTP in the development of advanced nuclear propulsion systems could be analogous to the role of the DC-3 in the development of advanced aviation. Progress made under the NTP project could also help enable high performance fission power systems and Nuclear Electric Propulsion (NEP). Guidance, navigation, and control of NTP may have some unique but manageable characteristics. [View Full Paper]

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ON THE IMPLEMENTATION OF MICROELECTROSPRAY PROPULSION SYSTEMS IN CUBESAT-CLASS SPACECRAFT

Matt Sorgenfrei,* Matt Nehrenz† and Robert E. Thomas‡

The integration of propulsion systems into CubeSat-class spacecraft is a key enabling technology for future science missions that require high levels of pointing stability or which operate beyond low Earth orbit. One promising technology for these very small spacecraft is microelectrospray propulsion (MEP) systems, due in part to their compact size and high specific impulse. While MEP systems display a number of ideal traits for spacecraft momentum management and low thrust translational maneuvers, much of the hardware is at a relatively low technology readiness level (TRL). NASA Ames Research Center and Glenn Research Center (GRC) have recently initiated a campaign to increase the TRL of candidate MEP systems for future flight projects. This test campaign is motivated by the performance requirements of a six-cube CubeSat operating in deep space, for which the MEP system will support detumble and momentum management. This paper will describe the candidate deep space mission, the software architecture required to drive the MEP system in a flight-like manner, and the test campaign that will be undertaken at GRC, including some preliminary test results.

[View Full Paper]

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DEVELOPMENT AND CHARACTERIZATION OF A MONOPROPELLANT MICROTHRUSTER WITH CUBESAT ATTITUDE CONTROL APPLICATIONS

M. Ryan McDevitt* and Darren L. Hitt†

Micropropulsion systems suitable for CubeSat applications are an area of active interest in the aerospace industry. In this work, numerical and experimental techniques are used to study a homogeneously catalyzed monopropellant microthruster. The monopropellant of interest is hydrogen peroxide (H_2O_2), while the homogeneous catalyst is an aqueous ferric chloride ($FeCl_3$) solution. To enhance microscale mixing of the monopropellant and the catalyst, the system is operated in the segmented flow regime through the injection of an inert gas. Numerical studies show that operating in this regime increases the operating temperature by more than 800% when compared to an equivalent laminar flow system. Flow visualization experiments of a 3D printed scale-model prototype of the microthruster show that the performance is sufficient to produce supersonic flow in a 2D converging-diverging nozzle. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL HARDWARE

SESSION VI

Many programs depend on heritage, but the future is advanced by those willing to design and implement new and novel architectures and technologies to solve the GN&C problems. This session was open to papers with topics concerning GN&C hardware ranging from theoretical formulations to innovative systems and intelligent sensors that will advance the state of the art, reduce the cost of applications, and speed the convergence to hardware, numerical, or design trade solutions. *Note: Advances in GN&C software are covered in Session IX.*

National Chairpersons:

Bryan Dorland
U.S. Naval Observatory

David Richie
U.S. Air Force Academy

Local Chairpersons:

Lee Barker
Lockheed Martin
Space Systems Company

Scott Francis
Lockheed Martin
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Michael Osborne
Lockheed Martin
Space Systems Company

The following paper was not available for publication:

AAS 15-077
Not Available

The following paper numbers were not assigned:

AAS 15-078 to -080

GOES-R DUAL ISOLATION*

Doug Freesland,† Delano Carter,‡ Jim Chapel,§ Brian Clapp,**
John Howat†† and Alexander Krimchansky‡‡

The Geostationary Operational Environmental Satellite-R Series (GOES-R) is the first of the next generation geostationary weather satellites, scheduled for delivery in late 2015. GOES-R represents a quantum increase in Earth and solar weather observation capabilities, with 4 times the resolution, 5 times the observation rate, and 3 times the number of spectral bands for Earth observations. With the improved resolution, comes the instrument suite's increased sensitive to disturbances over a broad spectrum 0-512 Hz. Sources of disturbance include reaction wheels, thruster firings for station keeping and momentum management, gimbal motion, and internal instrument disturbances. To minimize the impact of these disturbances, the baseline design includes an Earth Pointed Platform (EPP), a stiff optical bench to which the two nadir pointed instruments are collocated together with the Guidance Navigation & Control (GN&C) star trackers and Inertial Measurement Units (IMUs). The EPP is passively isolated from the spacecraft bus with Honeywell D-Strut isolators providing attenuation for frequencies above ~5 Hz in all six degrees-of-freedom. A change in Reaction Wheel Assembly (RWA) vendors occurred very late in the program. To reduce the risk of RWA disturbances impacting performance, a secondary passive isolation system manufactured by Moog CSA Engineering was incorporated under each of the six 160 Nms RWAs, tuned to provide attenuation at frequencies above ~50 Hz. Integrated wheel and isolator testing was performed on a Kistler table at NASA Goddard Space Flight Center. High fidelity simulations were conducted to evaluate jitter performance for four topologies: 1) hard mounted no isolation, 2) EPP isolation only, 2) RWA isolation only, and 4) dual isolation. Simulation results demonstrate excellent performance relative to the pointing stability requirements, with dual isolated Line of Sight (LOS) jitter < 1 μrad.
[View Full Paper]

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* Any opinions, findings, conclusions or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration or the National Aeronautics and Space Administration.

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ASTRO APS STAR TRACKER OPERATIONS ON ALPHASAT

U. Schmidt* and T. Fiksel†

In July 2013 the ASTRO APS autonomous star tracker on board of Alphasat was reliably brought into the geo-transfer orbit on its maiden flight by an Ariane 5 launcher. This in-orbit qualification of a novel star tracker product was realized by a Private Public Partnership between ESA and Inmarsat who owns and operates the satellite as part of its geostationary communication satellites fleet. The ASTRO APS star tracker is one of four technology demonstration payloads, named TDP6 on board of Alphasat. In addition to the nominal delivery of attitude- and angular rate data to the spacecraft control computer, the star tracker serves also for the initial pointing acquisition of the Laser Communication Terminal which is another technology demonstration payload TDP1 provided by TESAT/Germany. The star tracker was switched ON a few hours after the launch. The whole geo-transfer orbit phase of tracking data could be monitored and stored for data evaluation purposes. This included Sun, Earth and Moon interferences and spacecraft dynamics during the apogee maneuvers as well as the passage through the radiation belts. With reaching the spacecraft Earth pointing attitude in the geo-synchronous mode we receive telemetry data packages with an update rate of 3sec all over the day and for the next 3years. This exclusive data access is part of the phase E contract with ESA for the in-orbit characterization of the ASTRO APS star tracker. The paper presents and discusses some of the most up to date in-orbit test results.
[View Full Paper]

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AAS 15-073

HYDRA STAR TRACKER FOR JUICE ENVIRONMENT

Matthieu Beaumel,[*] Frédéric Gorog,[*] Benoît Gelin,[*] Laurent Nicollet,[*] Lionel Oddos-Marcel,[*] Massimo Palomba[†] and Pierre Pourrouquet[‡]

The Jupiter Icy Moon Explorer (JUICE) is an ESA mission whose aim is to study the Jovian system; Jupiter itself, its moons (Europa, Ganymede and Callisto) and the magnetosphere. The mission profile imposes considerable radiation constraints on the spacecraft, which are uncommon in typical space programs due to the Jupiter magnetic moment which is the largest of the solar system (almost 20 000 times more than the Earth). It results in a high total dose exposure at electronic parts level (factor ten with regards to typical GEO missions), high number of Single Event Effects and internal charging effects.

For this challenging mission, Sodern has been contracted by the European Space Agency (ESA) to identify and reduce the risks for an APS STR used in expected JUICE environment. (ESA contract 4000109972). For this activity Sodern will implement on the generic HYDRA star tracker the modifications identified in a precursor activity (ESA contract 40001011530) and manufacture an EQM to validate them by testing.

The generic HYDRA is the multiple head CMOS Active Pixel Sensor (APS) star tracker developed by Sodern. It achieved TRL-9 after being launched successfully aboard the French Spot-6 Earth observation satellite on September 9th 2012. HYDRA is composed of two physical units, Electronic Units (EU) for communication management, power supply and attitude computation, and up to four Optical Heads (OH) for image acquisition and video pre-processing. Such architecture allows for the protection of the Electronic Units by the spacecraft internal shielding while the Optical Heads are outside. In the frame of this activity, the configuration assumed for JUICE consists of two EU (one in cold redundancy) and three OH.

A comprehensive analysis has been performed to assess suitability of the HYDRA Star Tracker with respect to the intense radiation of the JUICE environment. This analysis encompassed total ionizing dose and shielding studies using Monte-Carlo methods, estimation of CMOS Image Sensor radiation-induced degradation using test data from electron and proton irradiations, assessment of the consequences of single event upsets and parasitic signal at focal plane level, calculation of the stray light levels caused by Cherenkov and luminescence effects in the optics, and an analysis of deep dielectric discharge issues.

In this paper Sodern presents adaptations of the HYDRA star tracker to turn it into a Radiation-Hard Star Tracker, able to cope with the extremely harsh Jovian environment and the expected performances. The key elements that allow the star tracker to withstand the worst case environment are the additional shielding around each optical head and the multiple head architecture of HYDRA. [View Full Paper]

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AAS 15-074

ESTADIUS: A DAYTIME ACCURATE ATTITUDE ESTIMATION SYSTEM FOR STRATOSPHERIC BALLOONS, BASED ON GYRO-STELLAR MEASUREMENT

Johan Montel,* Frédéri Mirc,* Etienne Pérot,† Yves André,* Jean Evrard,* Pierre Etcheto,* Muriel Saccoccio* and Nicolas Bray*

ESTADIUS is an autonomous, accurate and daytime attitude estimation system, for stratospheric balloons that require a high level of attitude measurement and stability. The system has been developed by CNES. ESTADIUS is based on star sensor and gyrometer data fusion within an extended Kalman filter. The star sensor is composed of a 16 MPixels visible-CCD camera and large aperture optics (135mm, f/1.8, FOV = 10°x15°) which provides very accurate stars measurements due to very low pixel angular size. This also allows detecting stars against a high sky background. The gyrometer is a FOG, with a performance class of 0.01°/h. The system is adapted to work down to an altitude of ~25km, even with high cinematic conditions. Key elements of ESTADIUS are: **daytime conditions use** (as well as night time), **autonomy** (automatic recognition of constellations), **high angular rate robustness** (a few deg/s thanks to the high performance of attitude propagation), **stray-light robustness** (thanks to a high performance baffle), **high accuracy** (<1'', 1σ). Four stratospheric qualification flights were very successfully performed in 2010/2011 and 2013/ 2014 in Kiruna (Sweden) and Timmins (Canada). ESTADIUS will allow long stratospheric flights with a unique attitude estimation system avoiding the restriction of the night/day conditions at launch. The first operational flight of ESTADIUS will be in 2015 for the **PILOT** scientific missions (led by IRAP and CNES in France). Further balloon missions such as CIDRE will use the system. ESTADIUS is probably the first autonomous, large FOV, daytime stellar attitude measurement system. This paper details the technical features and in-flight results. [View Full Paper]

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USAFA'S EYASSAT^3 AND HAMSTER BALL: INNOVATIVE TOOLS FOR PRACTICAL, HANDS-ON ATTITUDE DYNAMICS AND CONTROL EDUCATION*

Ayesha Hein,† David J. Richie,‡ Michael D. Sobers,§ Rebecca Esselstein,† Daniel R. Jones† and Paul Vergez**

Due to their high-density performance wrapped in a relatively small package, small cube-shaped satellites known as "CubeSats" have increased in popularity. Meanwhile, a fundamental satellite design topic crucial to a CubeSat's success is pointing (attitude) dynamics and control. It is therefore paramount that future CubeSat designers master both of these topics. The US Air Force Academy educates such future CubeSat designers through two courses, *Space Systems Engineering* and *Spacecraft Attitude Dynamics and Control*. Building on this need, both courses are implementing brand-new EyasSat^3 demonstration CubeSats and their companion attitude control hardware ground test tools, including a "hamster ball" spherical air-bearing platform and a Helmholtz cage, in order to teach CubeSat fundamentals in a three-dimensional environment similar to space. More specifically, EyasSat^3's are equipped with twelve light-detecting photo resistors (or "photo cells"), a three-axis magnetometer, a three-axis rate sensor unit, three single-axis torque rods, and three reaction/momentum wheels. Using these attitude control actuators and sensors as its foundation, an ongoing effort aims to craft complementary MATLAB analytical and C-based execution software tools for both feed forward control and feedback attitude estimation. So doing enables this system's employment in classrooms in the short-term with an eye to future USAF Academy course projects and activities in the longer term. These systems' effectiveness lies in the inherent, hands-on, tangible 3-D illustration incumbent with their use—imprinting the concepts onto cadet brains and thereby making these cadets more impactful members of the future DoD Space Cadre.

Building on the above needs, this paper, details the USAF Academy efforts to teach cadets to learn by doing attitude dynamics, determination, and control through employing EyasSat^3 satellites in free-standing configurations as well as integrated into the spherical air-bearing "hamster ball" system. The long-term promise these systems afford render EyasSat^3 a fantastic tool for illustrating, assessing, and predicting three-dimensional CubeSat motion. [View Full Paper]

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XACT – A NEW GENERATION OF NANO GN&C TECHNOLOGY

Daniel Hegel* and Matthew Baumgart†

Blue Canyon Technologies (BCT) has developed a complete nano GN&C sub-system, that supports a range of spacecraft, from CubeSats to microsats, and larger. The BCT XACT (fleXible Attitude Control Technology) represents a new generation of GN&C technology, in which an entire precision-pointing GN&C subsystem is integrated into a single 10x10x5cm package, and delivered fully assembled, programmed, and ready to use "out of the box", much like lap-top computers and smart phones today. The BCT XACT is an innovative and highly integrated design that provides 3-axis, stellar-based attitude determination and control with unprecedented pointing performance (0.003 deg, 1-sigma for two axes, 0.007 deg for the 3rd axis), and a powerful and flexible attitude command system that supports a wide range of pointing needs. XACT allows a more efficient spacecraft design, thereby maximizing the volume available for payload opportunities, and increasing overall spacecraft affordability, reliability, and utility. Features of XACT include: a nano star tracker with integrated stray-light baffle; 3 low-jitter reaction wheels; 3 torque rods; MEMS IMU; MEMS magnetometer; miniature sun sensor pyramid; integrated processor and electronics board; auto-generated flight software, including star identification, Kalman filter, attitude and momentum control, and orbit propagation (with interfaces for optional GPS). Whereas XACT was initially design for CubeSats, it is flexible in that it can control (as it will for upcoming missions) much larger spacecraft, simply by utilizing larger external actuators.
[View Full Paper]

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RECENT EXPERIENCES IN GUIDANCE, NAVIGATION AND CONTROL I

SESSION VII

This session focused on recent experiences in spaceflight GN&C, providing a forum to share insights gained through successes and failures. Discussions typically include GN&C experiences ranging from Earth orbiters to interplanetary spacecraft. This session is a traditional part of the conference and has shown to be most interesting and informative.

National Chairpersons:

Brett Smith
NASA Jet Propulsion Laboratory

Nic Mardle
ESA Operations Center

Local Chairpersons:

Suraj Rawal
Lockheed Martin
Space Systems Company

Ellis King
Charles Stark Draper Laboratory

The following paper was not available for publication:

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(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 15-086 to -090

AAS 15-081

THERMALLY-CONSTRAINED FUEL-OPTIMAL ISS MANEUVERS

Sagar Bhatt,[*] Andrew Svecz,[†] Abran Alaniz,[‡] Jiann-Woei Jang,[§] Louis Nguyen[**] and Pol Spanos[††]

Optimal Propellant Maneuvers (OPMs) are now being used to rotate the International Space Station (ISS) and have saved hundreds of kilograms of propellant over the last two years. The savings are achieved by commanding the ISS to follow a pre-planned attitude trajectory optimized to take advantage of environmental torques. The trajectory is obtained by solving an optimal control problem. Prior to use on orbit, OPM trajectories are screened to ensure a static sun vector (SSV) does not occur during the maneuver. The SSV is an indicator that the ISS hardware temperatures may exceed thermal limits, causing damage to the components. In this paper, thermally-constrained fuel-optimal trajectories are presented that avoid an SSV and can be used throughout the year while still reducing propellant consumption significantly. [View Full Paper]

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GLOBAL PRECIPITATION MEASUREMENT MISSION LAUNCH AND COMMISSIONING

Nikesha Davis,[*] Keith DeWeese,[*] Melissa Vess,[*] James R. O'Donnell, Jr.[†] and Gary Welter[‡]

During launch and early operation of the Global Precipitation Measurement (GPM) Mission, the Guidance, Navigation, and Control (GN&C) analysis team encountered four main on-orbit anomalies. These include: (1) unexpected shock from Solar Array deployment, (2) momentum buildup from the Magnetic Torquer Bars (MTBs) phasing errors, (3) transition into Safehold due to albedo induced Course Sun Sensor (CSS) anomaly, and (4) a flight software error that could cause a Safehold transition due to a Star Tracker occultation. This paper will discuss ways GN&C engineers identified the anomalies and tracked down the root causes. Flight data and GN&C on-board models will be shown to illustrate how each of these anomalies were investigated and mitigated before causing any harm to the spacecraft. On May 29, 2014, GPM was handed over to the Mission Flight Operations Team after a successful commissioning period. Currently, GPM is operating nominally on orbit, collecting meaningful scientific data that will significantly improve our understanding of the Earth's climate and water cycle.
[View Full Paper]

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NEOSSAT: MICROSATELLITE BASED SPACE SITUATIONAL AWARENESS

Stefan Thorsteinson,[*] Robert (Lauchie) Scott[†] and Brad Wallace[†]

The Near-Earth Object Surveillance Satellite (NEOSSat) microsatellite is a dual mission space telescope performing asteroid detection and Space Situational Awareness (SSA) experiments on high Earth orbit Resident Space Objects (RSOs). NEOSSat was launched on 25 February 2013 into a 786 km dawn-dusk sun synchronous orbit. The microsatellite payload is a 15cm aperture Maksutov-Cassegrain optical telescope, which serves as a dual use scientific instrument and star tracker. NEOSSat's dual missions pose challenging attitude requirements; sub-arcsecond stability, frequent pointing changes, and track rate mode (TRM) slews matching the apparent motion of RSOs up to 60 arcseconds/s. This paper identifies the lessons learned during the lengthy commissioning phase of the satellite and outlines the methodology for metric processing of recently acquired TRM imagery. [View Full Paper]

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AAS 15-085

THREE MID-MISSION IMPROVEMENTS TO MARS SCIENCE LABORATORY SURFACE ATTITUDE ESTIMATION ACCURACY*

Stephen F. Peters,† Steven M. Collins,‡ C. Anthony Vanelli,§ Matthew L. Robinson,** James F. Montgomery‡ and Shawn C. Johnson‡

Of all the contributions to attitude and pointing error in the Curiosity rover on Mars, only those from clock drift and gyroscope propagation increase over time. A single update on sol 647 to the onboard model of planetary motion both corrected for accumulated clock drift error and compensated for future clock drift. A flight software update on sol 481 added an accelerometer-only mode for updating attitude, eliminating accumulation of gyroscope propagation error when updating attitude during arm activities. The adoption of an operational pattern of following each drive with an accelerometer-based correction to attitude eliminated the roll and pitch components of gyroscope propagation error accumulated during drives. With these three improvements, only the yaw component of gyroscope propagation error grows from sol to sol.
[View Full Paper]

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LOW-THRUST MISSION PLANNING

SESSION VIII

The Low-Thrust Trajectories Mission Planning session offered an exciting opportunity to examine the state of the art in low-thrust mission design. The session focused on the applications of low-thrust technology to enable new classes of missions, such as Dawn's mission to Vesta and Ceres, Hayabusa II's mission to asteroid 1999 JU3, the Asteroid Redirect Mission (ARM) concepts, and even GOCE's mission in a very low Earth orbit. Low-thrust missions involve new and different challenges, compared to conventional missions, due to the extended burn durations and the interactions of the spacecraft with the propulsion system. Solar electric propulsion technology is advancing rapidly and the mission design community is working to discover the new opportunities it provides.

National Chairpersons:

Nathan Strange
NASA Jet Propulsion Laboratory

Michael Elsperman
The Boeing Company

Local Chairpersons:

Jeff Parker
University of Colorado at Boulder

Shawn McQuerry
Lockheed Martin
Space Systems Company

The following paper numbers were not assigned:

AAS 15-096 to -100

MISSION DESIGN FOR A CREWED EARTH-VENUS-MARS FLYBY MISSION USING SOLAR ELECTRIC PROPULSION

Stijn De Smet,[*] Jeffrey S. Parker,[†]
Jonathan F. C. Herman[*] and Ron Noomen[‡]

This paper discusses the preliminary design of a crewed Mars flyby mission using Solar Electric Propulsion. The research is a follow-up of studies in which it has been shown that new launch windows can be opened that would have been impossible to achieve using only chemical propulsion. This paper will investigate to what extent different total time of flights could improve a crewed Mars flyby mission. Furthermore, this paper will investigate other mission concepts such as an added Venus flyby.
[View Full Paper]

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AAS 15-092

OPTIMAL CONTINUOUS THRUST MANEUVERS FOR SOLVING 3D ORBIT TRANSFER PROBLEMS

Robyn M. Woollands,[*] Ahmad Bani Younes,[†] Brent Macomber,[*] Xiaoli Bai[‡] and John L. Junkins[§]

We simulate hybrid thrust transfers to rendezvous with space debris in orbit about the Earth. The hybrid thrust transfer consists of a two-impulse maneuver at the terminal boundaries, which is augmented with continuous low-thrust that is sustained for the duration of the flight. This optimal control problem is formulated using the path approximation numerical integration method, Modified Chebyshev Picard Iteration, which converges over a domain of about 1/3 of an orbit. This method differs from traditional two-point boundary value solvers in that it is not a shooting method. We make use of a "warm start" computed by using the two-impulse solution. We find that when continuous thrust is "turned off", the solution to the optimal control formulation reduces to the two-impulse two-point boundary value problem, with zero thrust coast. This study seeks to determine which thrust method is best suited for a specific transfer: two-impulsive or hybrid? For some transfers we observe a reduced terminal ΔV cost for the hybrid thrust relative to the two-impulse, and for others it may be increased. This depends on the relative orbits and the initial phasing of the satellites. Extremal field maps are generated for distinguishing globally optimal from infeasible and sub-optimal orbit maneuver regions. The computations in this paper were done via serial computation, however the structure of the algorithms is ideally suited for parallel algorithms. [View Full Paper]

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LOW-ENERGY, LOW-THRUST TRANSFERS BETWEEN EARTH AND DISTANT RETROGRADE ORBITS ABOUT THE MOON

Jonathan F. C. Herman* and Jeffrey S. Parker†

This paper discusses the use of Gauss-Lobatto collocation methods as applied to solving low-energy, low-thrust transfers from Low Earth Orbit to lunar Distant Retrograde Orbits. The methods used are described, and an initial guess in the form of a ballistic six month LEO-DRO transfer is introduced. Using parameters corresponding to modern day SEP technology, a transfer is designed that is a month shorter, using only minimal amounts of propellant. Furthermore, gravity assists at the Moon were autonomously introduced within the optimization, leading to a complex solution that differs significantly from the initial guess. This demonstrates the utility of collocation methods for solving complex trajectory problems, such as low-energy, low-thrust transfers. The optimized SEP transfer is illustrated, and compared against the ballistic reference trajectory. [View Full Paper]

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LINEAR COVARIANCE ANALYSIS FOR PROXIMITY OPERATIONS AROUND ASTEROID 2008 EV5

Cinnamon A. Wright,* Sagar Bhatt,† David Woffinden,†
Matthew Strube‡ and Chris D'Souza§

The NASA initiative to collect an asteroid, the Asteroid Robotic Redirect Mission (ARRM), is currently investigating the option of retrieving a boulder from an asteroid, demonstrating planetary defense with an enhanced gravity tractor technique, and returning it to a lunar orbit. Techniques for accomplishing this are being investigated by the Satellite Servicing Capabilities Office (SSCO) at NASA GSFC in collaboration with JPL, NASA JSC, LaRC, and Draper Laboratory, Inc. Two critical phases of the mission are the descent to the boulder and the Enhanced Gravity Tractor demonstration. A linear covariance analysis is done for these phases to assess the feasibility of these concepts with the proposed design of the sensor and actuator suite of the Asteroid Redirect Vehicle (ARV). The sensor suite for this analysis includes a wide field of view camera, LiDAR, and an IMU. The proposed asteroid of interest is currently the C-type asteroid 2008 EV5, a carbonaceous chondrite that is of high interest to the scientific community. This paper presents an overview of the linear covariance analysis techniques and simulation tool, provides sensor and actuator models, and addresses the feasibility of descending to the surface of the asteroid within allocated requirements as well as the possibility of maintaining a halo orbit to demonstrate the Enhanced Gravity Tractor technique. [View Full Paper]

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SEP-ENABLED ESPA-CLASS SATELLITE FOR NEAR-EARTH APPLICATIONS

William D. Deininger,[*] Scott Mitchell,[†] Scott Enger,[‡] Bryce Unruh,[§] Waldy K. Sjauwenwa[**] and Melissa L. McGuire[††]

Ball Aerospace & Technologies Corp. participated in a Space Act Agreement with NASA GRC to determine the feasibility of accommodating Solar Electric Propulsion (SEP) on an ESPA-class spacecraft. The BCP-100 bus was used as the baseline to leverage its flight heritage (STPSat-2 and STPSat-3, with GPIM under development). The study approach focused on minimizing changes to the existing bus design by modifying only what was necessary to accommodate the SEP system (structures, thermal and harnessing). This approach maintains high heritage and minimizes the amount of non-recurring engineering required for the bus. High heritage components are also selected for the 200 W SEP system including an off-the-shelf xenon tank, Hall effect thruster and cathode, and xenon feed control, allowing future development funding to be focused on a PPU compatible with the existing BCP-100 low voltage (28 V) power bus. The results of the study show a BCP-100 can be modified to accommodate meaningful SEP capability while meeting the mass and volume constraints for an ESPA launch. The Hall thruster SEP system produces ~1500 m/s ΔV with 20 kg of xenon propellant. This paper summarizes the BCP-100 design and capabilities, status of the heritage flight and in-development programs and summarizes how the BCP-100 is adapted to include SEP. Mission options starting in both LEO and GTO were explored and are discussed. The BCP-100 can accommodate enough SEP capability to allow the orbit to be raised or lowered anywhere within LEO or change the inclination up to 10° from a LEO starting point. From a GTO starting point, an elliptical orbit with a high perigee is also possible.
[View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL SOFTWARE

SESSION IX

The GN&C hardware is often dependent on successful and innovative GN&C software. This session was open to all GN&C software ranging from on orbit software used to drive or process data, ground software used for operations or simulation software used to test, validate or develop GN&C systems. This session aimed to highlight GN&C software from all aspects. *Note: Advances in GN&C hardware applications are covered in Session VI.*

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AAS 15-109 to -110

AAS 15-101

LATTICE BOLTZMANN METHOD FOR SPACECRAFT PROPELLANT SLOSH SIMULATION

Jeb S. Orr,* Joseph F. Powers† and Hong Q. Yang‡

A scalable computational approach to the simulation of propellant tank sloshing dynamics in microgravity is presented. In this work, we use the lattice Boltzmann equation (LBE) to approximate the behavior of two-phase, single-component isothermal flows at very low Bond numbers. Through the use of a non-ideal gas equation of state and a modified multiple relaxation time (MRT) collision operator, the proposed method can simulate thermodynamically consistent phase transitions at temperatures and density ratios consistent with typical spacecraft cryogenic propellants, for example, liquid oxygen. Determination of the tank forces and moments relies upon the global momentum conservation of the fluid domain, and a parametric wall wetting model allows tuning of the free surface contact angle. Development of the interface is implicit and no interface tracking approach is required. Numerical examples illustrate the method's application to predicting bulk fluid motion including lateral propellant slosh in low-g conditions.
[View Full Paper]

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AAS 15-102

TARANIS: AOCS OVERVIEW AND FLEXIBLE MODE ISSUES DURING ORBIT MANEUVER

J. Lefebve, E. Bellouard, L. Boissier,
S. Tremolière, S. Mary and C. Bastien-Thiry[*]

The paper will first introduce TARANIS and its mission objectives. Then, after a brief description of the AOCS design, it will focus on the flexible mode issues. Indeed with 4 masts, one arm and a rotating solar array, the AOCS control has to deal with a lot of flexible modes. The most constraining phase is the orbit control phase when the AOCS subsystem uses 4 1N hydrazine thrusters both to modify the satellite orbit and to control its attitude by off-modulation. A specific study has been performed to specify the flexible mode characteristics (forbidden frequencies, damping factor) and to identify the risk to excite them with the thrusters commands. This study has been performed first with a theoretical control stability approach and then with a dedicated simulator of the complete AOCS control loop. [View Full Paper]

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PILOTING AND GUIDANCE ALGORITHMS FOR AUTONOMOUS LANDING

Carlos Perez-Montenegro[*] and Enrico Canuto[†]

The paper describes piloting and guidance algorithms for a landing probe mounting an axial camera. Piloting aims to update the guidance target on the basis of hazard maps of the landing terrain, which are provided by suitable camera data elaboration (not treated here). To be generic, the hazard maps used for simulated test were artificially synthesized. [View Full Paper]

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AAS 15-105

ATTITUDE DETERMINATION AND CONTROL APPROACH TO ACHIEVE CO-LOCATED MICROWAVE RADIOMETER AND GPS RADIO OCCULTATION MEASUREMENTS ON A NANOSATELLITE

Weston Marlow, Anne Marinan, Kathleen Riesing, Tam Nguyen, Kerri Cahoy, James Byrne, Andrew Kennedy, Ryan Kingsbury, Zachary Decker, Timothy Cordeiro, Stephen Shea,[*] William J. Blackwell, Gregory Allen, Christopher Galbraith, R. Vincent Leslie, Idahosa Osaretin, Michael Shields, David Toher, Peter Klein, Erik Thompson, Michael DiLiberto,[†] Rebecca Bishop, James Bardeen, David Ping, Susan Lui and Tamitha Mulligan[‡]

The Microwave Radiometer Technology Acceleration (MiRaTA) mission is a 3U CubeSat that was selected by the NASA Earth Science Technology Office to demonstrate a new tri-band passive microwave radiometer for sensing temperature, water vapor, and cloud ice and the use of a GPS radio occultation (GPSRO) experiment for temperature calibration, as well as supporting subsystem technologies such as the attitude determination and control system (ADCS). These new sensing modalities can dramatically enhance the capabilities of future weather and climate sensing architectures. The MiRaTA mission will demonstrate high fidelity, well-calibrated radiometric sensing from a nanosatellite platform. The radiometer and GPSRO technology elements are currently at TRL5 but will be advanced to TRL7 at mission conclusion. This demonstration mission, nominally to be launched and deployed into a 600 km sun-synchronous orbit in 2016, will mark the first implementation of temperature and humidity radiometric sounding and GPSRO atmospheric sounding on a single 3U CubeSat.

The attitude determination and control performance of the MiRaTA nanosatellite is critical to mission success. A deliberate slow pitch-up maneuver from radiometer nadir pointing to 90-105° and back will be periodically executed to permit the radiometer and GPSRO observations to sound overlapping volumes of atmosphere where sensitivity, calibration, and dynamic range are optimal. Enabling this agility with a nanosatellite platform requires an ADCS capable of performing, among other tasks, successful detumble after deployment and maintaining three-axis stable pointing to a goal of ±1° of accuracy during science operations throughout the mission. We describe the sensor and actuator selection, flight software development, end-to-end modeling techniques, and hardware-in-the-loop testing planned for MiRaTA. [View Full Paper]

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ADVANCES IN ORION'S ON-ORBIT GUIDANCE AND TARGETING SYSTEM ARCHITECTURE

Sara K. Scarritt,* Thomas Fill† and Shane Robinson*

NASA's manned spaceflight programs have a rich history of advancing onboard guidance and targeting technology. In order to support future missions, the guidance and targeting architecture for the Orion Multi-Purpose Crew Vehicle must be able to operate in complete autonomy, without any support from the ground. Orion's guidance and targeting system must be sufficiently flexible to easily adapt to a wide array of undecided future missions, yet also not cause an undue computational burden on the flight computer. This presents a unique design challenge from the perspective of both algorithm development and system architecture construction. The present work shows how Orion's guidance and targeting system addresses these challenges. On the algorithm side, the system advances the state-of-the-art by: (1) steering burns with a simple closed-loop guidance strategy based on Shuttle heritage, and (2) planning maneuvers with a cutting-edge two-level targeting routine. These algorithms are then placed into an architecture designed to leverage the advantages of each and ensure that they function in concert with one another. The resulting system is characterized by modularity and simplicity. As such, it is adaptable to the on-orbit phases of any future mission that Orion may attempt. [View Full Paper]

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AIRBORNE SIMULATION OF LAUNCH VEHICLE DYNAMICS

Christopher J. Miller,[*] Jeb S. Orr,[†] Curtis E. Hanson[*] and Eric T. Gilligan[‡]

In this paper we present a technique for approximating the short-period dynamics of an exploration-class launch vehicle during flight test with a high-performance surrogate aircraft in relatively benign endoatmospheric flight conditions. The surrogate vehicle relies upon a nonlinear dynamic inversion scheme with proportional-integral feedback to drive a subset of the aircraft states into coincidence with the states of a time-varying reference model that simulates the unstable rigid body dynamics, servodynamics, and parasitic elastic and sloshing dynamics of the launch vehicle. The surrogate aircraft flies a constant pitch rate trajectory to approximate the boost phase gravity turn ascent, and the aircraft's closed-loop bandwidth is sufficient to simulate the launch vehicle's fundamental lateral bending and sloshing modes by exciting the rigid body dynamics of the aircraft. A novel control allocation scheme is employed to utilize the aircraft's relatively fast control effectors in inducing various failure modes for the purposes of evaluating control system performance. Sufficient dynamic similarity is achieved such that the control system under evaluation is configured for the full-scale vehicle with no changes to its parameters, and pilot-control system interaction studies can be performed to characterize the effects of guidance takeover during boost. High-fidelity simulation and flight-test results are presented that demonstrate the efficacy of the design in simulating the Space Launch System (SLS) launch vehicle dynamics using the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center Fullscale Advanced Systems Testbed (FAST), a modified F/A-18 airplane (McDonnell Douglas, now The Boeing Company, Chicago, Illinois), over a range of scenarios designed to stress the SLS's Adaptive Augmenting Control (AAC) algorithm.
[View Full Paper]

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HIGH ANGULAR RATE DETERMINATION ALGORITHM BASED ON STAR SENSING

Fabio Curti,[*] Dario Spiller,[†] Luigi Ansalone,[‡] Simone Becucci,[§] Dorico Procopio,[§] Franco Boldrini,[§] Paolo Fidanzati[§] and Gianfranco Sechi[**]

The paper focuses on the problem of determining high rate angular velocity directly from star-tracker measurements. A fully gyroless solution would result in reduced AOCS costs and complexity. The aim is to extend the maximum angular rate magnitude up to 20 deg/s or more, at which at least a first, coarse rate determination could still be performed. At a high angular rate, the star-tracker acquires images with streaks related to the stars in the FOV of the sensor. This work aims to develop a High Rate Mode to be implemented on Selex ES' APS based Star Tracker line of products (AA-STR and SPACESTAR). The APS sensor line read-out time introduces an image distortion in which the streaks are stretched or shortened depending if the star moves in the image plane, in the same direction or in the opposite direction of the line read-out. This effect is not negligible because the distortion induces an error of about 25% in the estimation of the length of the streak. In the paper, an analysis of the APS read-out distortion is presented in order to reduce the error in the determination of the magnitude of the angular velocity. The angular velocity direction is identified using a geometrical approach. A numerical simulator has been developed to simulate operative scenarios in order to test the algorithm. Finally, numerical results are shown assuming that only one star is detectable and considering angular rates from 10 deg/s to 25 deg/s. At lower rates, different algorithms (simpler) will be used for the rate determination. These are not discussed in this paper. The Rate Mode under development will allow to achieve reliable and accurate rate measurements necessary for de-tumbling satellites and for star trackers to switch back to tracking mode. [View Full Paper]

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PROXIMITY OPERATIONS

SESSION X

Proximity operations imply maneuvering of a vehicle near another body. This session aimed to explore the GN&C aspects of spacecraft operations in the vicinity of other spacecraft, including maneuvering, rendezvousing, and docking, and landers maneuvering near planetary surfaces. Papers may include GN&C algorithms, system studies, space and test flight experience, and sensors that provide the necessary data for proximity operations.

National Chairpersons:

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Reuben Rohrschneider
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The following paper numbers were not assigned:

AAS 15-119 to -120

RAVEN: AN ON-ORBIT RELATIVE NAVIGATION DEMONSTRATION USING INTERNATIONAL SPACE STATION VISITING VEHICLES

Matthew Strube,[*] Ross Henry,[†] Eugene Skelton,[‡] John Van Eepoel,[§] Nat Gill[*] and Reed McKenna[**]

Since the last Hubble Servicing Mission five years ago, the Satellite Servicing Capabilities Office (SSCO) at the NASA Goddard Space Flight Center (GSFC) has been focusing on maturing the technologies necessary to robotically service orbiting legacy assets–spacecraft not necessarily designed for in-flight service. Raven, SSCO's next orbital experiment to the International Space Station (ISS), is a real-time autonomous relative navigation system that will mature the estimation algorithms required for rendezvous and proximity operations for a satellite-servicing mission. Raven will fly as a hosted payload as part of the Space Test Program's STP-H5 mission, which will be mounted on an external ExPRESS Logistics Carrier (ELC) and will image the many visiting vehicles arriving and departing from the ISS as targets for observation. Raven will host multiple sensors: a visible camera with a variable field of view lens, a long-wave infrared camera, and a short-wave flash lidar. This sensor suite can be pointed via a two-axis gimbal to provide a wide field of regard to track the visiting vehicles as they make their approach. Various real-time vision processing algorithms will produce range, bearing, and six degree of freedom pose measurements that will be processed in a relative navigation filter to produce an optimal relative state estimate. In this overview paper, we will cover top-level requirements, experimental concept of operations, system design, and the status of Raven integration and test activities. [View Full Paper]

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A 6-DOF POSE INITIALIZATION STRATEGY FOR LIDAR-BASED NON-COOPERATIVE NAVIGATION

John O. Woods,*, John A. Christian† and Thomas A. Evans‡

LIDAR sensors have recently been explored for their utility in proximity operations, namely autonomous rendezvous and docking. Specific areas of interest within the space community include navigation relative to natural objects (e.g., asteroids) or artificial objects (e.g., satellites). In both cases, the observed objects are not equipped with some form of navigation aid, and are thus referred to as "noncooperative." Most LIDAR-based pose estimation techniques rely on the iterative closest point (ICP) algorithm, which requires a good initial estimate of pose in order to converge on a near-correct solution. However, the initial guess may be hard to obtain, and poor ICP solutions — which may be fed in as the initial guesses for future ICP executions — can be propagated into detrimental pose estimates later in the rendezvous, creating an unrecoverable situation. Demonstrated in this work is a technique borrowed from personal robotics, known as Oriented, Unique, and Repeatable Clustered Viewpoint Feature Histograms (OUR-CVFH), which simultaneously recognizes an object and estimates its 6-DOF pose on the basis of point clouds generated from LIDAR sensors. OUR-CVFH is robust to many partial occlusions. The technique is also fast, running in under a second, and could allow for periodic re-initialization (or checking) of the Kalman filter. It is possible to characterize when and where OUR-CVFH is likely to fail (such as degeneracy of object views), and to account for this knowledge both in determination of an approach trajectory and in choosing when to re-initialize the filter. Also described is an OpenGL "pseudo-sensor," developed for quickly generating 3D point cloud "sensor images." [View Full Paper]

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GUIDANCE, NAVIGATION, AND CONTROL ALGORITHMS FOR CUBESAT FORMATION FLYING

Christopher W. T. Roscoe,[*] Jason J. Westphal,[*] Stephen Lutz[*] and Trevor Bennett[†]

The development of accurate and robust guidance, navigation, and control (GNC) algorithms which can run efficiently on low-power processors using passive sensors, while placing an emphasis on spacecraft autonomy, is one of the primary problems faced in developing on-board rendezvous, proximity operations, (RPO) and docking software for CubeSat formation flying. This paper outlines the design of the innovative RPO GNC system and underlying algorithms used to solve these issues for the CPOD mission. Absolute and relative navigation is performed using a dual-inertial state Extended Kalman Filter, and impulsive guidance and control are performed in a fuel-optimal state-space maneuver targeting formulation using differential mean orbital elements. The GNC software is implemented in a flexible, efficient software architecture which manages on-board RPO functions in a multi-threaded, prioritized process environment.
[View Full Paper]

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COMPARISON OF APPROACHES TO RELATIVE NAVIGATION USING GLOBAL POSITIONING DURING FLIGHT OF THE CYGNUS SPACECRAFT*

Alex Manka†

When using the Global Positioning System (GPS) to navigate spacecraft relative to each other, it is common to use a Relative GPS (RGPS) estimate that is independent of solutions resulting from the individual GPS receivers of each spacecraft. Compared to using individual GPS solutions, this approach trades simplicity for improved accuracy. The efficacy of this trade is evaluated with results from flight of Orbital's Cygnus spacecraft, which uses RGPS during delivery of cargo to the International Space Station (ISS). [View Full Paper]

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AAS 15-115

DESIGN AND PRELIMINARY TESTING OF THE INTERNATIONAL DOCKING ADAPTER'S PERIPHERAL DOCKING TARGET

Christopher W. Foster,[*] Johnathan M. Blaschak,[†] Erin A. Eldridge,[‡] Jack P. Brazzel[§] and Peter T. Spehar[**]

The International Docking Adapter's Peripheral Docking Target (PDT) was designed to allow a docking spacecraft to judge its alignment relative to the docking system. The PDT was designed to be compatible with relative sensors using visible cameras, thermal imagers, or Light Detection and Ranging (LIDAR) technologies. The conceptual design team tested prototype designs and materials to determine the contrast requirements for the features. This paper will discuss the design of the PDT, the methodology and results of the tests, and the conclusions pertaining to PDT design that were drawn from testing. [View Full Paper]

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AAS 15-116

A SAMPLING-BASED APPROACH TO SPACECRAFT AUTONOMOUS MANEUVERING WITH SAFETY SPECIFICATIONS

Joseph A. Starek,* Brent Barbee† and Marco Pavone‡

This paper presents a method for *safe* spacecraft autonomous maneuvering that leverages robotic motion planning techniques to spacecraft control. Specifically, the scenario we consider is an in-plane rendezvous of a chaser spacecraft in proximity to a target spacecraft at the origin of the Clohessy-Wiltshire-Hill frame. The trajectory for the chaser spacecraft is generated in a receding-horizon fashion by executing a sampling-based robotic motion planning algorithm named Fast Marching Trees (FMT), which efficiently grows a tree of trajectories over a set of probabilistically-drawn samples in the state space. To enforce safety, the tree is only grown over *actively safe samples*, from which there exists a one-burn collision avoidance maneuver that circularizes the spacecraft orbit along a collision-free coasting arc and that can be executed under potential thruster failures. The overall approach establishes a provably-correct framework for the *systematic* encoding of safety specifications into the spacecraft trajectory generation process and appears promising for *real-time* implementation on orbit. Simulation results are presented for a two-fault tolerant spacecraft during autonomous approach to a single client in Low Earth Orbit. [View Full Paper]

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ANGLES-ONLY NAVIGATION RANGE OBSERVABILITY DURING ORBITAL RENDEZVOUS AND PROXIMITY OPERATIONS

David K. Geller[*] and T. Alan Lovell[†]

This paper focuses on several new recent developments regarding the question of angles-only range observability during orbital rendezvous and proximity operations. In the past, the Cartesian formulation of the Clohessy-Wiltshire equations have been used to study the relative orbital navigation problem. Unfortunately, the natural curvature of the orbit is lost in this formulation and as such the angles-only relative navigation problem appears to be unobservable. In cylindrical coordinates, however, the orbit curvature information is maintained and range observability is confirmed. Even more dramatic is the effect of camera center-of-mass offset on range observability at small separation distances. In this regime, it is shown that the relative position and velocity can be observed and determined from three observations using a simple non-iterative algorithm. Based on these conclusions, an end-to-end angles-only relative navigation architecture encompassing close-in proximity operations, intermediate range rendezvous operations, and long range operations is proposed. [View Full Paper]

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AAS 15-118

NONLINEAR REPRESENTATIONS OF SATELLITE RELATIVE MOTION EQUATIONS USING CURVILINEAR TRANSFORMATIONS

Alex C. Perez* and T. Alan Lovell†

A novel set of solutions for satellite relative motion is developed using nonlinear transformations from curvilinear coordinate frames. These nonlinear representations capture the curvature of an orbit and the relative dynamics due to the curvilinear nature of the coordinate frame. Nonlinear polynomial approximate solutions are also derived using a 2nd order Taylor series expansion of the nonlinear equations. Example trajectories are generated and compared using the novel set of solutions. These new solutions can be used for many different satellite relative motion applications such as maneuver/targeting applications and initial relative orbit determination algorithms.
[View Full Paper]

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SMALL BODY PROXIMITY OPERATIONS

SESSION XI

GN&C operations in weak gravitational environments are mission-enabling for innovative science missions to small bodies such as asteroids and comets. GN&C in this environment is challenging due to the unusual navigation data types, non-conservative force modeling for guidance and trajectory prediction and the precision required for hyperbolic flyby, hovering, landing, and sample return operations. This session explored the GN&C challenges, designs, predicted performance and recent experiences for a variety of current and planned missions to small bodies.

National Chairpersons:	Dan Scheeres University of Colorado at Boulder
	Shyam Bhaskaran NASA Jet Propulsion Laboratory
Local Chairpersons:	Bill Frazier formerly of Ball Aerospace & Technologies Corp. currently, NASA Jet Propulsion Laboratory
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The following paper numbers were not assigned:

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AAS 15-121

FLYBY-ONLY SCIENCE OPERATIONS FOR AN ASTEROID EXPLORATION MISSION

D. J. Scheeres,[*] S. Van wal[†] and S. Tardivel[‡]

Orbital operations at small bodies can be challenging for mission planning purposes due to the large uncertainties in a target asteroids shape, size, mass and rotation rate. Even if these are known based on ground observations, the overall environment may also be challenging from an orbit stability point of view, especial for a binary asteroid. For an asteroid with a sufficiently small total size and mass, however, orbital mechanics approaches can be eschewed in favor of performing multiple flybys of the body at low speeds, performing a "turn around" maneuver every few days to revisit the body. In this paper this mission approach is explored in more detail, and in terms of observations and gravity field measurements of the central body. Considerations will also be explored for the deployment of surface packages using such an approach. It will be shown that this approach to mission operations at small asteroids forms another possible close proximity solution in addition to the already explored orbital and hovering approaches used by the NEAR and Hayabusa missions, respectively. [View Full Paper]

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ROSETTA NAVIGATION AT COMET CHURYUMOV-GERASIMENKO

Shyam Bhaskaran,[*] Stephen Broschart, Don Han, Nick Mastrodemos, Bill Owen, Ian Roundhill, Brian Rush, Jonathon Smith,[†] David Surovik,[‡] Frank Budnik and Vicente Companys[§]

On August 6, 2014, the European Space Agency's Rosetta mission arrived at comet Churyumov-Gerasimenko to mark a new era in comet exploration. After a series of orbits which took it progressively closer to the nucleus, the Philae lander was released from the Rosetta orbiter and touched down on the surface of the comet on November 12, 2014. Navigation of Rosetta, including the landing of Philae, was especially challenging due to several factors, including the use of terrain-relative optical navigation, the central body being a highly irregularly shaped object with unknown mass distribution, and an unknown coma environment. The responsibility for mission design and navigation of Rosetta resides with the Flight Dynamics group at the European Space Operations Center; through a collaborative arrangement, navigation specialists at the Jet Propulsion Laboratory also performed a parallel effort to reconstruct the spacecraft's orbit from approach through the Philae landing. In this paper, we describe JPL's methods and results in determining the orbit of Rosetta and the Philae lander. [View Full Paper]

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OPTICAL NAVIGATION FOR THE ROSETTA MISSION

Nickolaos Mastrodemos,[*] Brian P. Rush[†] and William M. Owen, Jr.[‡]

JPL's participation in ESA's Rosetta mission to comet 67P/Churyumov-Gerasimenko includes a parallel navigation effort in which JPL conducts navigation operations along with ESA and compares orbit solutions and estimated cometary parameters. Optical navigation, begun during approach to the comet and continuing through the orbit phases, is an integral part of that effort. We describe the optical navigation operations, methodology and key results for star-relative image processing during approach, and landmark tracking on orbit. [View Full Paper]

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THE APPLICATION OF OPTICAL BASED FEATURE TRACKING TO OSIRIS-REx ASTEROID SAMPLE COLLECTION*

Ryan Olds,† Alexander May,‡ Courtney Mario,§ Reid Hamilton,** Chris Debrunner†† and Kalle Anderson‡‡

The Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer (OSIRIS-REx) mission is designed to rendezvous with the asteroid Bennu, where it will study the topography, mineralogy, and chemistry of the asteroid. The primary objective of the mission is to contact the surface of Bennu, collect a sample of regolith and return the sample to Earth. The Natural Feature Tracking (NFT) subsystem is being developed to aid in sample collection by providing an autonomous optical based orbit determination capability. NFT will utilize knowledge of known asteroid features to correlate with observed features, which are captured in real-time imaging of the surface. Residuals measured between expected feature location and measured feature location are used to update a Kalman Filter estimating orbital position and velocity. This paper will introduce the Natural Feature Tracking concept and describe the general design approach. Further, the application of NFT to the OSIRIS-REx mission objectives will be described. [View Full Paper]

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OSIRIS-REX TOUCH-AND-GO (TAG) NAVIGATION PERFORMANCE

Kevin Berry,[*] Peter Antreasian,[†] Michael C. Moreau,[*] Alex May[‡] and Brian Sutter[‡]

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission is a NASA New Frontiers mission launching in 2016 to rendezvous with the near-Earth asteroid (101955) Bennu in late 2018. Following an extensive campaign of proximity operations activities to characterize the properties of Bennu and select a suitable sample site, OSIRIS-REx will fly a Touch-And-Go (TAG) trajectory to the asteroid's surface to obtain a regolith sample. The paper summarizes the mission design of the TAG sequence, the propulsive maneuvers required to achieve the trajectory, and the sequence of events leading up to the TAG event. The paper also summarizes the Monte-Carlo simulation of the TAG sequence and presents analysis results that demonstrate the ability to conduct the TAG within 25 meters of the selected sample site and ±2 cm/s of the targeted contact velocity. The paper describes some of the challenges associated with conducting precision navigation operations and ultimately contacting a very small asteroid. [View Full Paper]

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BENNU ASTEROID PROXIMITY OPERATIONS NAVIGATION USING A LUENBERGER OBSERVER WITH FLASH LIDAR RANGE MEASUREMENTS

Oliver K. Walthall* **and Keith Mahoney***

The Bennu asteroid sample return mission requires a safe approach to a surface with highly variable terrain, as well as accurate imminent contact prediction to facilitate successful sample collection. To achieve these rendezvous objectives, a Luenberger observer using Flash LIDAR range measurements is the approach taken by OSIRIS-REx. Successful design and performance depend on appropriately addressing nuances to LIDAR-based navigation, such as the interaction between closed-loop LIDAR intensity control and the corresponding effects on state estimation accuracy. [View Full Paper]

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THE SMALL-BODY DYNAMICS TOOLKIT AND ASSOCIATED CLOSE-PROXIMITY NAVIGATION ANALYSIS TOOLS AT JPL*

Stephen B. Broschart,† Matthew Abrahamson,† Shyam Bhaskaran,† Eugene G. Fahnestock,† Reza R. Karimi,† Gregory Lantoine,† Thomas A. Pavlak† and Loic Chappaz‡

Over the past several years, an ecosystem of MATLAB©-based tools has been developing at NASA's Jet Propulsion Laboratory (JPL) for early-mission analysis of encounter-phase navigation at primitive bodies. These tools increasingly draw from a common implementation of capabilities known as the Small-Body Dynamics Toolkit (SBDT). Fundamentally, the SBDT provides support for trajectory integration and geometric analysis of the environment, providing force models (gravity, solar pressure, comet outgassing), equations of motion, polyhedron shape utilities, altitude calculations, occultation checking, and more. Using the capabilities of the SBDT, analysis tools for mapping performance analysis (PB-CAGE), navigation performance analysis (AutoNAV), and trajectory design space characterization (SBMCT) have been developed. This paper provides a brief overview of the SBDT and these associated analysis tools.
[View Full Paper]

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AAS 15-128

REAL-TIME MAPPING AND LOCALIZATION UNDER DYNAMIC LIGHTING FOR SMALL-BODY LANDINGS

Dylan Conway* and John L. Junkins†

Small-body landing missions present difficult challenges to Guidance, Navigation, and Control (GNC) systems. A typical mission profile makes a distinction between a mapping phase and a terminal navigation phase. In the mapping phase, analysts on the ground process spacecraft sensor data to generate a geometric and visual model of the body. This model is used to pick a particular landing site. Then during the terminal navigation stage, the spacecraft must autonomously drive itself towards the landing site using the map. There are two major hurdles here. The first hurdle is that the visual appearance of the map will change as the direction to the sun changes in both the body-frame and the sensor-frame. The second hurdle is that smaller landing hazards on the ground only become visible due to improved spatial resolution as the spacecraft gets closer to the surface and are therefore not a part of the map made from greater standoff range. This paper presents a method to clear both of these hurdles. An algorithm to sequentially estimate the full geometry and texture of the local terrain about the landing site is developed. With this information and an estimate of sensor-to-inertial and body-to-inertial pose available, the terrain is efficiently rendered under the actual lighting and estimated relative sensor pose conditions. The rendered images are then compared to sensor images to perform pose estimate updates. Details of the map parameterization, rendering algorithm, pose estimation method, and filtering are presented. Laboratory experiments in a simulated scene with ground truth data are used to validate the algorithm. [View Full Paper]

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RECENT EXPERIENCES IN GUIDANCE, NAVIGATION AND CONTROL II

SESSION XII

This session focused on recent experiences in spaceflight GN&C, providing a forum to share insights gained through successes and failures. Discussions typically include GN&C experiences ranging from Earth orbiters to interplanetary spacecraft. This session is a traditional part of the conference and has shown to be most interesting and informative.

National Chairpersons:	Brett Smith NASA Jet Propulsion Laboratory
	Nic Mardle ESA Operations Center
Local Chairpersons:	Jim Chapel Lockheed Martin Space Systems Company
	Kristen Francis Lockheed Martin Space Systems Company

The following paper numbers were not assigned:

AAS 15-138 to -140

KEPLER 2 MISSION OVERVIEW AND RECENT EXPERIENCE

Dustin Putnam* **and Douglas Wiemer***

The Kepler spacecraft began the first science campaign of its new mission, K2, on May 30, 2014. K2 continues the original Kepler mission, collecting high precision photometry for exoplanet and astro-seismology research, but now the vehicle is oriented so that the photometer collection fields are centered on the ecliptic plane. This paper presents an overview of the K2 mission architecture, how the spacecraft is stabilized using two reaction wheels, the use and performance of the reaction control thrusters, pointing results for the first and second science campaigns, and forward looking plans for pointing improvements. Pointing stability in the new mission is approximately 200 milli-arc-seconds 1σ, and absolute pointing accuracy is better than 1 arc-second 1σ.
[View Full Paper]

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AAS 15-132

INITIAL ON-ORBIT PERFORMANCE OF THE MAVEN SPACECRAFT

Dale Howell,[*] Mark Johnson,[*] William Pisano[†] and Jason Wynn[‡]

MAVEN (Mars Atmosphere and Volatile Evolution Mission), part of the NASA Mars Scout Program, is a 3-axis stabilized spacecraft which launched on November 18th, 2013 and arrived at Mars on September 21st, 2014. MAVEN's primary role is to study the remaining atmosphere of Mars and to gain a better understanding of its evolution. To facilitate these objectives, the MAVEN spacecraft maintains an elliptical orbit with a periapsis altitude below that of current Martian orbiters where detailed atmospheric measurements can be made by a suite of instruments separated from the main spacecraft bus by a deployable 1 meter boom. The MAVEN GN&C system is designed to overcome the unique navigation and pointing challenges associated with flying through the dynamic Martian atmosphere on every orbit. This paper will discuss some of the early performance of MAVEN's GN&C subsystem from the orbit insertion burn through the initial on-orbit checkout and calibration phase. [View Full Paper]

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AAS 15-133

GAIA: FIRST YEAR FLIGHT OPERATIONS EXPERIENCE

F. Di Marco,[*] J. Marie,[†] D. Milligan[‡] and A. Rudolph[§]

Gaia is a European Space Agency's (ESA) science cornerstone mission and was launched on 19-Dec-2013 on a Soyuz-ST-B from Kourou, French Guyana. The Gaia mission relies on the proven principles of ESA's Hipparcos mission to solve one of the most difficult yet deeply fundamental challenges in modern astronomy: to create an extraordinarily precise three-dimensional map of sources up to visual magnitude 20. This is estimated to be over one billion sources throughout our Galaxy and beyond. The demanding performance requirements led to a very stable thermal/mechanical design with no moving parts and an operational Lissajous orbit around the second Earth-Sun Lagrange point. The Attitude and Orbit Control System (AOCS) in particular includes two novel aspects: precise rate measurements derived through the telescope optics and Charge Coupled Devices (CCDs) are used in the AOCS control loop, and actuation via a cold gas micro propulsion system for attitude control and solar radiation pressure compensation. These allow the highly demanding stability requirements to be met. In addition, an Monomethylhydrazine (MMH)/ Nitrogen Tetroxide (NTO) chemical propulsion system is used for fall back modes and orbit maintenance and control. This paper describes the first year flight operations experience of Gaia. [View Full Paper]

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POST-FLIGHT ANALYSIS OF THE GUIDANCE, NAVIGATION AND CONTROL PERFORMANCE DURING ORION EXPLORATION FLIGHT TEST 1*

Andrew Barth,† Harvey Mamich‡ and Brian Hoelscher§

The first test flight of the Orion Multi-Purpose Crew Vehicle presented additional challenges for guidance, navigation and control as compared to a typical re-entry from the International Space Station or other Low Earth Orbit. An elevated re-entry velocity and steeper flight path angle were chosen to achieve aero-thermal flight test objectives. New IMU's, a GPS receiver, and baro altimeters were flight qualified to provide the redundant navigation needed for human space flight. The guidance and control systems must manage the vehicle lift vector in order to deliver the vehicle to a precision, coastal, water landing, while operating within aerodynamic load, reaction control system, and propellant constraints. Extensive pre-flight six degree-of-freedom analysis was performed that showed mission success for the nominal mission as well as in the presence of sensor and effector failures. Post-flight reconstruction analysis of the test flight is presented in this paper to show whether that all performance metrics were met and establish how well the pre-flight analysis predicted the in-flight performance.
[View Full Paper]

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GLN-MAC INITIALIZATION APPROACH AND NAVIGATION SOLUTION AS APPLIED TO LDSD*

Brian R. Tibbetts,† Eric Blood,‡ Steve Sell† and Jeff Benton§

The recent Low Density Supersonic Decelerator (LDSD) Supersonic Flight Dynamics Test (SFDT) vehicle flew from the Pacific Missile Range Facility (PMRF) on Kauai, Hawaii. This SFDT flight tested two entry technologies, a 6-meter supersonic inflatable aerodynamic decelerator (SIAD), which was deployed at Mach 4, and a supersonic disksail parachute, which was deployed at Mach 2.75. In order to test these entry technologies in Mars-relevant conditions, the technologies must fly through a representative mach and dynamic pressure regime. To accomplish that, the test vehicle was hoisted under a balloon up to an altitude of 36 km. At this point, the test vehicle separated from the balloon and began its primary mission under its own propulsion. A critical aspect of meeting the test conditions was to deploy the technologies at the correct velocities, to within 30m/s. Several challenges existed to accomplish this level of accuracy, including initialization of the IMU (GLN-MAC) while in a pendulum-motion under the balloon, the use of a magnetometer in a untested configuration for heading, and loss of GPS solutions at vehicle spin-up, requiring ded-reckoned navigation throughout the flight. This paper describes the challenges and our solutions to initialization, producing a navigated velocity for event triggering, operations, and the in-flight performance of the system. [View Full Paper]

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AAS 15-136

MSL CRUISE ATTITUDE CONTROL FLIGHT EXPERIENCE AND IMPLICATIONS FOR MARS 2020*

Steven M. Collins,† John C. Essmiller,† Erisa K. Hines,‡ A. Miguel San Martin§ and Frederick Serricchio†

The spectacular landing of the Mars Science Laboratory "Curiosity" rover in August 2012 was made possible by the near perfect delivery of the vehicle to the planned entry conditions after a 8-month interplanetary cruise. Using a spin-stabilized attitude control architecture based on the earlier Mars Exploration Rovers and Mars Pathfinder missions, MSL executed 4 trajectory corrections, 22 turns to maintain power and communications and 18 turns in support of in-flight alignments and calibrations. To enable use of a guided, lifting entry, cruise ACS was also called on to perform a high-reliability precision initialization of the entry vehicle's onboard inertial navigation system just before landing. Along with other surprises, cruise operations were complicated by an early problem with the spacecraft flight computer which prevented use of the onboard star scanner for the first few months of flight. During this important period, ACS activities were accomplished using a combination of sun-only modes and ground based attitude determination. This paper outlines the MSL cruise attitude control system and relates our flight experience during operations, describing some of the challenges faced during the mission and the techniques and system features used to over-come them. We also present a performance assessment and several lessons learned with relevance to Mars 2020 and other future missions using the MPF/MER/MSL cruise architecture.
[View Full Paper]

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AAS 15-137

THE FIRST THREE MANEUVERS DURING MESSENGER'S LOW-ALTITUDE SCIENCE CAMPAIGN

Sarah H. Flanigan,[*] Madeline N. Kirk,[†] Daniel J. O'Shaughnessy,[‡] Stewart S. Bushman[§] and Paul E. Rosendall[**]

Periapsis-raising orbit-correction maneuvers (OCMs) are required during the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft's second extended mission (XM2) to delay Mercury surface impact and to maximize the time that the spacecraft spends at altitudes as low as 15 km. The first OCM of XM2 was implemented to ensure that fuel remaining in main fuel tank 2 (FT2) would be accessible in the future. The second OCM depleted the fuel remaining in FT2 and demonstrated the use of helium gas pressurant as a propellant. A specialized autonomy scheme was developed to detect and respond to prolonged gas ingestion. Performance of the first three OCMs facilitated an extension of MESSENGER operations several weeks past the projected XM2 surface impact date of 28 March 2015. The ability to impart velocity change (ΔV) using pressurization gas has increased the mission's ΔV capability. [View Full Paper]

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POSTER SESSION

SESSION 0

The Poster Session offered a unique forum for authors and interested parties to discuss relevant topics. Posters did not require an accompanying written paper. However, authors who wished to have their work published in the proceedings submitted written papers along with the poster. The Poster Session was available for viewing every day in the main conference room.

Local Chairpersons: Alex May
Lockheed Martin
Space Systems Company

The following papers were not available for publication:

AAS 15-001
Multi-spacecraft Autonomous Positioning System: Conceptual Architecture, Simulation Analysis, Hardware Testing, and Continued Development, Evan Anzalone (NASA MSFC) (Poster Only)

AAS 15-005
Two-Axis Fast Mirror Technology, Islam Shawki (Raytheon) (Poster Only)

AAS 15-006
CubeSat Proximity Operations Demonstration (CPOD-Mission: Concept of Operations for Miniaturized Rendezvous, Proximity Operations, and Docking, Jason J. Westphal, Christopher W. T. Roscoe, Marco Villa, Ehson Mosleh, Dean R. Hawes (Applied Defense) (Poster Only)

AAS 15-007
Generalized Covariance Minimization Algorithm for the Continuous Extended Kalman Filter for Nonlinear Plants and Sensor Models, Kevin Hernandez and James D. Turner (Texas A&M University) (Poster Only)

AAS 15-010
OSIRIS-REx Asteroid Contact Dynamics From First Principles, Will Hafer (Lockheed Martin) (Poster Only)

The following paper numbers were not assigned:

AAS 15-011 and -020

AAS 15-002

AVOIDING HIGH-GAIN ANTENNA OCCLUSIONS AND FLOPS IN MARS SCIENCE LABORATORY SURFACE OPERATIONS*

Stephen F. Peters,† C. Anthony Vanelli,‡ William C. Allen,§ Steven M. Collins, James F. Montgomery** and Evgeniy Sklyanskiy††**

A rover occlusion is a part of the spacecraft which blocks the high-gain antenna's view of the Earth, interfering with communication. A flop is a change of kinematic solution in the middle of an Earth track, temporarily breaking the communications link. When the Mars Science Laboratory rover is level and the Earth is near the horizon, the Earth is occluded for 55 percent of rover headings. When the rover is level and the Earth is near zenith, a flop is required to continue tracking for 44 percent of rover headings. These constraints and two tools used in everyday tactical operations to help rover planners choose unoccluded, flop-free end-of-drive headings are described.
[View Full Paper]

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AAS 15-003

AN ERROR BUDGET FOR POINTING AT SURFACE FEATURES FROM CLOSE RANGE*

Stephen F. Peters†

Spacecraft instrument pointing performance is often characterized by a single number: radial angular error, three sigma. In support of the spacecraft design process, pointing error budgets allocate allowable contributions to this error from the sensors, actuators, and portions of spacecraft structure that affect pointing accuracy. When pointing the Mars Science Laboratory ChemCam Laser-Induced Breakdown Spectrometer at a surface feature, the error of interest is the distance of the laser spot from the feature on the surface. The footprint of error on the surface depends not only on the overall radial angular error, but also on the distance to the surface feature. Translational distortions within the spacecraft also affect the error footprint. The effective origin of error is defined, and a mathematical formulation for computing pointing error budgets in terms of radial distances from a surface feature is presented. [View Full Paper]

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METHODOLOGY FOR THE IN-FLIGHT ESTIMATION OF COLLECTED REGOLITH SAMPLE MASS ON THE OSIRIS-REX MISSION*

Michael Skeen,† Alexander May,‡ Ryan Olds‡ and Timothy Linn§

The Origins, Spectral Interpretations, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) mission is the third NASA New Frontiers Program mission and will launch in September 2016 to study the near-Earth asteroid Bennu. After several months of proximity operations to characterize the asteroid, the OSIRIS-REx spacecraft flies a Touch-And-Go (TAG) trajectory to the asteroid's surface to collect at least 60 g of pristine regolith sample for Earth return. In order to verify the success of the TAG event, the spacecraft will perform an in-flight measurement of the sample mass collected. This paper presents the design and analysis of the methodology that will be employed to perform this measurement. The OSIRIS-REx spacecraft will perform several slew maneuvers to utilize an in-flight measurement of spacecraft inertia as demonstrated by the Cassini mission based on the principle of conservation of momentum. These maneuvers are designed to estimate the spacecraft inertia about a single axis in two configurations of the sampling mechanism both before and after the TAG event. These measurements will be processed to isolate the inertia contribution due to the collected regolith sample mass. An overview is presented of the analysis performed to characterize the performance of the Guidance, Navigation, and Control algorithms designed to measure the spacecraft inertia and to describe the potential sources of error in the designed method. The method's measurement uncertainty of 48.7 g meets the mission requirement of 90 g. [View Full Paper]

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STATE TRANSITION MATRIX FOR PERTURBED ORBITAL MOTION USING MODIFIED CHEBYSHEV PICARD ITERATION

Julie Read,* Ahmad Bani-Younes,† John L. Junkins‡ and James D. Turner§

The Modified Chebyshev Picard Iteration (MCPI) method has recently proven to be more efficient for a given accuracy than the most commonly adopted numerical integration methods, as a means to solve for perturbed orbital motion. This method utilizes Picard iteration, which generates a sequence of path approximations, and discrete Chebyshev Polynomials, which are orthogonal and also enable both efficient and accurate function approximation. The nodes consistent with discrete Chebyshev orthogonality are generated using cosine sampling; this strategy also reduces the Runge effect and as a consequence of orthogonality, there is no matrix inversion required to find the basis function coefficients. The MCPI algorithms considered herein are parallel-structured so that they are immediately well-suited for massively parallel implementation with additional speedup.

MCPI has a wide range of applications beyond ephemeris propagation, including the propagation of the State Transition Matrix (STM) for perturbed two-body motion. A solution is achieved for a spherical harmonic series representation of earth gravity (EGM2008), although the methodology is suitable for application to any gravity model. Included in this representation is a derivation of the second partial derivatives of the normalized, Associated Legendre Functions, which is given and verified numerically.
[View Full Paper]

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PARALLEL MODIFIED CHEBYSHEV PICARD ITERATION FOR ORBIT CATALOG PROPAGATION AND MONTE CARLO ANALYSIS

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Modified Chebyshev Picard Iteration is a numerical method for integrating Ordinary Differential Equations. MCPI in a serial setting has been shown to improve the speed of orbit propagation computations by orders of magnitude over current state-of-the-practice methods. This paper presents a parallel MCPI framework for integrating the equations of perturbed orbital motion. It consists of a parallelized set of serial MCPI instances running in a compute cluster environment. Additionally, a first order Taylor series gravity approximation method is presented that allows MCPI to propagate orbits in the vicinity of a reference trajectory with vastly decreased computational cost. Two applications of parallel propagation are demonstrated, satellite catalog propagation, and Monte Carlo analysis of a system of particles. [View Full Paper]

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