GUIDANCE, NAVIGATION, AND CONTROL 2016

Edited by
David A. Chart

American Astronautical Society

Volume 157

ADVANCES IN THE ASTRONAUTICAL SCIENCES

GUIDANCE, NAVIGATION, AND CONTROL 2016

Front Cover Illustration:

OSIRIS-REx is a NASA New Frontiers mission to study the Bennu asteroid. Key objectives are to characterize and map the asteroid, collect a sample of surface material and return the sample to Earth for analysis. The OSIRIS-REx mission is managed by NASA Goddard Spaceflight Center. The principle investigator is Dante Lauretta from the University of Arizona, Tucson, Arizona. Lockheed Martin Space Systems in Littleton, Colorado built the spacecraft. Image credit: Lockheed Martin.

Frontispiece:

Final assembly of the OSIRIS-REx spacecraft in a Lockheed Martin cleanroom located in Littleton, Colorado. The payload deck is shown in the image, which includes electro-optical (EO), infrared (IR), x-ray, and lidar imaging payloads. The EO & lidar imagers are used by the Flight Dynamics and GN&C teams to navigate the spacecraft in proximity to asteroid Bennu. The large high gain antenna is shown on the left and the Sample Return Capsule (SRC) is located in the center of the payload deck. Image credit: Lockheed Martin.


LOCKHEED MARTIN
OSIRIS-REx

GUIDANCE, NAVIGATION, AND CONTROL 2016

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FOREWORD

HISTORICAL SUMMARY

The annual American Astronautical Society Rocky Mountain Guidance, Navigation 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 jointly came up with the idea of convening a broad spectrum of experts in the field for a fertile exchange of aerospace control ideas. At about this same time, Dan DeBra and Lou Herman had discussed a similar plan.

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 more than 20 years. The 2016 Conference was the 39th Annual AAS Rocky Mountain Guidance, Navigation 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, strictly adhered to until 2013, involved no parallel sessions and two three-hour technical/tutorial sessions. 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 and expanded.

A tradition from the beginning and retained until 2014 had been the Conference banquet. 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.”
2011 Joe Tanner, Former Astronaut; Senior Instructor, University of Colorado, “Building Large Objects in Space.”
2012 Greg Chamitoff, Ph.D., 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.
2016 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, "Opticsin 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, AerospaceHuman 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

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

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"

2016 1st Place: Brian C. Fields, Shawn M. Kocis, Kerri L. Williams, and Mark Karpenko, "Hardware-in-the-Loop Simulator for Rapid Prototyping of CMG-Based Attitude Control Systems."

2nd Place: Ann Dietrich and Jay W. McMahon, "Error Sensitivities for Flash LIDAR Based Relative Navigation around Small Bodies"

3rd Place: Kevin D. Anderson, Darryll J. Pines, and Suneel I. Sheikh, "Investigation of Combining X-ray Pulsar Phase Tracking Estimates to Form a 3D Trajectory"

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 high school students, 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. This event was continued in 2016, building on the prior year and again reaching over 100 high school and college students.

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, navigation 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	139
2013	Lisa Hardaway	181
2014	Alexander May	180
2015	Ian Gravseth	195
2016	David Chart	216

The AAS Guidance, Navigation 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, Navigation 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, navigation and control experts for years to come.

On behalf of the Conference Committee and the Section,

Dr. David A. Chart
Lockheed Martin Space Systems Company
Denver, Colorado

PREFACE

This year marked the 39th anniversary of the AAS Rocky Mountain Section's Guidance and Control Conference. It was held in Breckenridge, Colorado at the Beaver Run Resort from February 5 – 10, 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 Lockheed Martin Space Systems' 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 a keynote address from Mike Gazarik, VP of Engineering at Ball Aerospace, followed by an impressive *Student Innovations in GN&C* session featuring a student competition with scholarship prizes. Following the student paper session, the conference hosted the 2nd annual STEM-SCAPE event, which introduced over 80 area high school students to careers in an aerospace engineering field. To cap off the day, the *Technical Exhibits* session was held Saturday afternoon. Nearly twenty companies and organizations participated with many hardware demonstrations as well as excellent technical interchanges between conferees, vendors, and family.

Other sessions during the conference examined the current state-of-the-art and other focus areas of interest to the GN&C community. The *GN&C Future Concepts* and *Future of Space* Servicing sessions were presented on Sunday morning. The *Advanced Access to Space* and *Miniaturization of GN&C* Components sessions took place on Sunday afternoon. Between the sessions, Frank Bauer presented a tutorial entitled *Beyond the Textbook: GNSS*.

Monday morning two concurrent sessions, *GNSS Precision PNT* and *Image-Based Optical Navigation* were held. During the mid-day, the AGI team presented a tutorial, *Beyond the Textbook: Simulating Observations to Assess OD Performance*. Monday evening featured the *Pioneers in GN&C and Astronautics* session.

Tuesday morning's parallel sessions included *Small Body Encounters* and the *Orion Special Session*. Tim Henderson, Charles Stark Draper Laboratory gave the tutorial *Beyond the Textbook: Space Precision Pointing, Tracking and Stabilization: A Holistic View of Instrumentation, Algorithms, and Applications*. The Tuesday evening sessions were *In Space Propulsion Innovations* and the ever-popular *Advances in GN&C*.

We were fortunate to have astronaut Jim Voss give an exciting presentation to the children visiting with us at the conference. We also had a daily *Poster Session* where posters were on display so attendees could speak one-on-one with the authors during breakfast, break periods and a special Sunday poster focus time.

Finally, Wednesday morning featured the popular closing session *Recent Experiences*. 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 39th 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 and Amy Delay 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. David A. Chart, Conference Chairperson
2016 AAS Guidance and Control Conference

CONTENTS

STUDENT INNOVATIONS IN GUIDANCE, NAVIGATION AND CONTROL

Session 1

National Chairpersons:

Tim Crain, Intuitive Machines

David Geller, Utah State University

Lt. Col. David Richie, United States Air Force Academy

Local Chairpersons:

Ian Gravseth, Ball Aerospace & Technologies Corp.

Jastesh Sud, Lockheed Martin Space Systems Company

The following paper numbers were not assigned:

AAS 16-019 to -030

AAS 16-011

INVESTIGATION OF COMBINING X-RAY PULSAR PHASE TRACKING ESTIMATES TO FORM A 3D TRAJECTORY

Kevin D. Anderson,* Darryll J. Pines† and Suneel I. Sheikh‡

X-ray pulsars are promising navigational aids for spacecraft. Phase tracking is a method that directly exploits the periodic nature of a pulsar signal and uses it to estimate a spacecraft's position. This method provides more frequent estimates than other navigation techniques that have been considered for use with x-ray pulsars, which generally rely on long observations to make a single estimate. The method used in this paper to phase track pulsar signals consists of breaking an observation of an individual pulsar into small blocks. The length of this block is chosen using a tradeoff that takes into account the pulsar and the trajectory of the spacecraft. Over each block a maximum likelihood estimator (MLE) pro-vides a phase estimate to a digital phase-locked loop (DPLL). Previous research has shown that a second-order phase model is needed for the MLE along with a third-order DPLL in order to successfully lock onto pulsar signals with low flux. In this paper a quick analytical method is presented to predict the threshold observation time necessary for the ML-estimates to approach the Cramer-Rao lower bound. This method is shown to work well for pulsars B1821-24 and B1937+21 as compared to time consuming empirical determinations of the threshold. An extended Kalman filter (EKF) framework is used to test different scenarios and pulsar combinations. Measurements are fed to the EKF based on the accuracies anticipated from PLL outputs locked onto each pulsar. Two different detector setups are tested. First a setup with three detectors is simulated, which allows for three pulsars to be phase-tracked simultaneously. Second a set-up with a single detector that switches between tracking pulsars depending on which are in view of the spacecraft. The Crab pulsar along with two lower flux MSPs, B1821-24 and B1937+21, are considered. This is the first simulated demonstration of using an EKF to combine simulated pulsar phase tracking measurement accuracies to form a three-dimensional tracking solution. Results are shown to be able to track position with accuracies on the order of a few kilometers for Earth-centered orbits and around 5 km error for heliocentric orbits. [View Full Paper]

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‡ Chief Research Scientist, ASTER Labs, Inc., 155 East Owasso Lane, Shoreview, Minnesota 55126, U.S.A.

AAS 16-012

SOLAR RADIATION PRESSURE APPLICATIONS ON GEOSTATIONARY SATELLITES

Patrick Kelly,[*] Richard S. Erwin,[†] Riccardo Bevilacqua[‡] and Leonel Mazal[§]

Taking advantage of the solar radiation pressure at geostationary orbits can provide a viable means of actuation for orbital control and can lead to propellantless satellite missions. Using only solar radiation pressure, it is possible to control the semi-major axis, eccentricity, inclination, or even perform satellite servicing missions. Utilizing attainably large solar sails, this paper will demonstrate possible methods for executing such maneuvers. [View Full Paper]

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[‡] Associate Professor, Mechanical and Aerospace Engineering, University of Florida.
[§] Postdoctoral Researcher, Mechanical and Aerospace Engineering, University of Florida.

AAS 16-013

A GEOMETRIC APPROACH TO SECOND-ORDER, CIRCULAR-REFERENCE SPACECRAFT RELATIVE MOTION

Lylia Benhacine,* Andrew Harris,† T. Alan Lovell‡ and Andrew J. Sinclair§

In studying spacecraft relative motion, linearized solutions have an advantage of simple geometry that can be intuitively visualized, but higher-order solutions have an advantage of improved accuracy. This paper presents an alternative approach to deriving these solutions using Carleman linearization. This approach provides insight into the nature of the solution via modal analysis. In particular, the no-drift condition is analyzed. Additionally, a geometric framework for analyzing the second-order solution is presented. The second-order solution is re-parameterized to derive a set of second-order relative orbit elements defined in terms of the Cartesian states. This yields a 22-element set that encapsulates the motions predicted by the second-order solution in a geometric fashion. [View Full Paper]

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AAS 16-014

HARDWARE-IN-THE-LOOP SIMULATOR FOR RAPID PROTOTYPING OF CMG-BASED ATTITUDE CONTROL SYSTEMS

Brian C. Fields,* Shawn M. Kocis,* Kerri L. Williams* and Mark Karpenko†

Control moment gyroscopes (CMGs) are the actuators of choice for agile spacecraft. While they are remarkably capable torquers, attitude control using CMGs is challenging since gimbal commands must be properly allocated in order to avoid control singularities in the momentum space. Heritage systems typically cannot utilize the full capability of a CMG array and are therefore operated within only a small region of the momentum envelope. The range of operation of CMG systems can, however, be extended through the development and implementation of new steering concepts to avoid singular states. To transition these new algorithms to practice, extensive simulation and ground testing is necessary. This paper describes a hardware-in-the-loop (HIL) simulator for rapid prototyping of CMG attitude control laws that has been developed by students at the Naval Postgraduate School. The HIL testbed is aimed at providing students and other researchers a platform for developing and testing new ideas for agile control of CMG spacecraft in a hardware-based laboratory environment. The results of several HIL experiments are presented to illustrate the functionality of the testbed, which allows real CMG hardware to be exercised against a numerical simulation of a spacecraft. [View Full Paper]

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LOW COST SPACECRAFT ATTITUDE DETERMINATION FOR CUBESAT TYPE MISSIONS

Vinicius Guimaraes Goecks,* Austin Probe,† Robyn Woollands,†
John E. Hurtado‡ and John L. Junkins§

We present a method for performing low cost attitude estimation for CubeSat type missions. Our algorithm uses measurements from a custom built sun sensor, a star camera, and inertial measurements. These sensing measurements are supplied in real-time to a Multiplicative Kalman Filter for the purpose of generating continuous attitude estimates. The testing and validation of this algorithm is done in the Land, Air, and Space Robotics Laboratory at Texas A&M University, using our custom three degrees-of-freedom attitude test-bed interfacing with a suspended target emulation pendulum. The algorithm is implemented using low cost commercial off-the-shelf hardware and open-source libraries for the required vision based localization. This low cost, low power and small-scale attitude estimation technology is ideal for use on CubeSats and ChipSats. Our algorithm is designed to be part of a suite of tools that is currently being developed at the lab for attitude estimation and control. [View Full Paper]

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AAS 16-016

RELATIVE SPACECRAFT NAVIGATION VIA INTER-SATELLITE RANGE MEASUREMENTS

Christian Rundberg[*] and T. Alan Lovell[†]

This paper demonstrates the feasibility of a novel range-based navigation system among a cluster of satellites. Determining the trajectory of one or more satellites in the cluster (referred to as deputies) relative to a reference satellite in the cluster (referred to as the chief) from only range measurements will be useful in missions where the satellites possess a communication link among them. This is essentially a relative orbit determination problem, whereby the relative position & velocity states of each deputy are to be estimated from the range measurements. This paper focuses on the initial relative orbit determination problem, whereby the trajectory is found that best fits the range measurements obtained, assuming a particular dynamic model. It is postulated that the Clohessy-Wiltshire relative motion solution may provide a feasible model for this purpose. Because this solution is closed-form, it may then be possible to obtain a closed-form solution to the overall relative orbit determination problem. The two main contributions of this paper are to derive an initial relative orbit determination algorithm for range-only and to investigate ambiguities in the problem that may exist. [View Full Paper]

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AAS 16-017

ERROR SENSITIVITIES FOR FLASH LIDAR BASED RELATIVE NAVIGATION AROUND SMALL BODIES

Ann Dietrich[*] and Jay W. McMahon[†]

Shape model errors and pointing errors are investigated when using flash LIDAR measurements for navigation in proximity to the asteroid, Itokawa. Three different shape model fidelities are presented, and their shape differences and resulting effects on the state estimation are studied. It was found that when using a shape model in the filter with a lower fidelity than the truth model, the state errors remained bounded. With pointing errors of $1\sigma=0.1°$ and $1\sigma=0.5°$ (1.7 mrad and 8.7 mrad), the state errors also remained bounded. The flash LIDAR images contained enough range measurements that the state errors did not deviate in the presence of the shape modeling and pointing errors.

[View Full Paper]

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AAS 16-018

NOVEL MAGNETIC FIELD TRACKING USING FALCONSAT-3 MAGNETOMETER ONLY MEASUREMENTS*

Christian Arnold,† Brian W. Kester‡ and David J. Richie§

The United States Air Force Academy's FalconSAT-3 (FS-3) is a cadet-built and operated satellite launched in 2007 to perform Department of Defense scientific research for the Space Test Program. In order to meet program objectives, it is important the satellite is controlled and stable in three axes. The satellite's angular rates were first stabilized in 2014 using a B-dot controller. This paper builds on the progress made during stabilization and explores the implementation of a new angular position control scheme on FS-3, designed to enable payload data collection by pointing the satellite's experiments panel in its required direction for the first time. Specifically, the payloads mounted on one of the satellite's side panels requires it point in the velocity (ram) direction within the customer's required accuracy. Currently, the satellite uses a 3-axis magnetometer and solar panel currents (during sunlight) for coarse attitude determination since its on-board sun sensors are not functioning properly. It also uses magnetic torque rods for pointing control in concert with its passively stable gravity gradient boom. A magnetometer-only measurement control scheme for commanding the torque rods is thus imperative to achieve payload data collection needs and is also critical during eclipse when pointing knowledge quality further degrades. Based on the satellite's limitations, this paper proposes a novel magnetometer-only control scheme for FalconSAT-3 to capitalize on its magnetometer and torque rods, then implements it on a classroom CubeSat demonstrator known as EyasSat3 and presents and analyzes these newly obtained results. [View Full Paper]

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GUIDANCE, NAVIGATION AND CONTROL FUTURE CONCEPTS

Session 3

National Chairperson:

Doug Freeland, NASA Goddard Space Flight Center

Local Chairpersons:

Tim Bevacqua, Lockheed Martin Space Systems Company

Dennis Nicks, Jr., Ball Aerospace & Technologies Corp.

The following papers were not available for publication:

AAS 16-031 (Paper Withdrawn)

AAS 16-035 (Paper Withdrawn)

AAS 16-036 (Paper Withdrawn)

AAS 16-037 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 16-039 to -040

AAS 16-032

GN&C DESIGN FOR AUTONOMOUS PAYLOAD RETURN FROM ISS

Shaun Stewart,[*] Wyatt Johnson,[†] Scott Tamblyn,[‡] Christina Chomel,[§] John Woods[**] and Tim Crain[††]

A fully autonomous spacecraft known as the Terrestrial Return Vehicle (TRV) was developed to enable rapid return of scientific payloads from the International Space Station (ISS). The TRV provides near-daily opportunities to return payloads to Earth and aims to enable more efficient utilization of the ISS as a national laboratory. The TRV was developed in partnership with NASA and is a mid-Lift/Drag (L/D) lifting body shape designed to transport up to 10 kg of cargo from low-Earth orbit (LEO). Once deployed from ISS, the vehicle determines its navigation state and identifies the earliest opportunity for deorbit and landing. Trajectory guidance during the on-orbit and entry phases of flight allow for 30 meter landing accuracy at the Earth. This paper provides an overview of the TRV guidance, navigation, and control (GN&C) systems that were developed to enable autonomous deorbit from LEO, guided entry, and precision landing at the Earth.

[View Full Paper]

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AAS 16-033

SPLIT-MANEUVER TARGETING BASED ON PSEUDO-LAMBERT TARGETING AND THE CLOHESSY-WILTSHIRE EQUATIONS

Nicholas G. Ortolano,[*] David K. Geller[†] and T. Alan Lovell[‡]

This paper presents a new method for reducing inertial and relative maneuver targeting errors using the Clohessy-Wiltshire equations. The new method, known as split-maneuver targeting, is developed by introducing a pseudo-chief reference frame between the initial orbit and the final target orbit. The method is applied to the inertial pseudo-Lambert targeting problem and the relative maneuver targeting problem for orbital rendezvous and proximity operations. [View Full Paper]

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AAS 16-034

GEO-HOSTED IMAGING SPECTROMETER

James F. Speed,[*] James L. Carr,[†] Homero L. Gutierrez[*] and Dennis Nicks[*]

The Tropospheric Emissions, Monitoring of Pollution (TEMPO) program is deploying a hosted GEO imaging spectrometer that measures daily air quality over a large geographic area. In this paper, we provide an overview of the mission and we detail instrument design challenges associated with being a hosted payload where spacecraft attitude control and jitter management is normally of less concern. We discuss the scan mechanism employed to cover the imaging spectrometer's field of regard and to reject host disturbances and minimize pointing errors. Finally, the ground support and mission operations are summarized, including image navigation and registration (INR) and tailoring of the scan commands for efficient coverage of Greater North America (GNA). [View Full Paper]

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AAS 16-038

ATTITUDE CONTROL PERFORMANCE ANALYSIS USING DISCRETIZED THRUSTER WITH RESIDUAL TRACKING

John Alcorn,* Hanspeter Schaub† and Scott Piggott‡

Some spacecraft rely on a cluster of thruster pairs for attitude control, momentum management, station keeping, and trajectory maneuvers. Most thrusters must be operated in an on-off control fashion. The minimum impulse bit, the smallest impulse the thruster can supply, is dictated by the minimum pulse duration of the thruster. Furthermore, the pulse duration command is discretized according to the servo frequency of the flight computer, effectively limiting the resolution of the commanded pulse duration. Each of these discrete aspects of the thruster dynamics presents a challenge when implementing a continuous control law for attitude stabilization or reaction wheel momentum management. Pulse duration residuals, that is, unimplemented thruster ON time, may be tracked and leveraged to better approximate a continuous implementation of the control law. A numerical analysis is presented of the trade space between minimum pulse duration and pulse duration resolution by characterizing performance in terms of steady state error and propellant usage in a Monte Carlo fashion. Furthermore, thruster-based torque uncertainties are taken into account to illustrate regimes where implementing the pulse residual tracking no longer impacts the final pointing performance. [View Full Paper]

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FUTURE OF SPACE SERVICING

Session 4

National Chairpersons:

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Brook Sullivan, Sullivan Analytics

Glenn Creamer, Naval Research Laboratory

Local Chairperson:

Alex May, Lockheed Martin Space Systems Company

The following paper was not available for publication:

AAS 16-043 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 16-048 to -050

AAS 16-041

SETTING THE STANDARDS FOR SATELLITE SERVICING*

Barry G. Miller†

The need for a new operating paradigm in space has never been more evident given the rapidly increasing reliance on space-based platforms to meet commercial, civil, and military demands. The long-standing approach of "launch, de-grade, and replace" as it pertains to constellation management is rapidly becoming obsolete as more capable and agile business models emerge to satisfy consumer demand for space-based services. Satellite servicing to extend the operational life or increase operational flexibility offers satellite owner/operators a near term option to better manage their respective constellations so long as it can be demonstrated to be safe, secure, and reliable. Lockheed Martin has undertaken a number of studies to examine the technical, operational, and regulatory requirements necessary to successfully execute servicing of existing satellites and the requirements for future "serviceable by design" satellites that represent the next generation of communication and sensing platforms. Preliminary standards for mission operations including rendezvous, proximity operations, capture, and stacked operations are presented. [View Full Paper]

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VISION NAVIGATION SENSOR (VNS) WITH ADAPTIVE ELECTRONICALLY STEERABLE FLASH LIDAR (ESFL)

Reuben R. Rohrschneider,[*] Carl Weimer,[†] James Masciarelli,[†] Mike Adkins and Jeanette Domber[‡]

Ball Aerospace has been developing Flash LIDAR systems for more than 7 years, and space qualified their first system on the Sensor Test for Orion Relative-navigation Risk Mitigation (STORRM) mission in May of 2011 on STS-134. The STORRM unit demonstrated the capabilities of the flash LIDAR system for cooperative relative navigation, but other applications exist, including science applications, landing risk mitigation on Earth and other planets, and non-cooperative rendezvous and capture of spacecraft for servicing. One key technology for making the flash LIDAR a more broadly applicable sensor is the addition of electronically steerable laser projection optics to provide flexibility in operations and to optimize the use of the limited number of photons available. This principle is important in any application where mass and power are limited commodities. The addition of Electronically Steerable Flash LIDAR (ESFL) capability to the VNS enables the system to offer the functionality of both scanning and flash LIDARs simultaneously, without any mechanisms. This improves the target acquisition range for non-cooperative targets while still providing the imaging capability at close range. This paper provides an overview of the Vision Navigation Sensor (VNS) flash LIDAR and the work towards a common navigation sensor that meets NASA's common specification through the addition of ESFL. Potential mass and volume reductions are also covered to balance the mass and volume required by ESFL. [View Full Paper]

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AAS 16-044

LADAR RANGE REFINEMENT USING BINARY SHIFT KEYING

Manoranjan Majji,* Bradley Sallee† and John L. Junkins‡

This paper presents some details pertaining to phase based range refinement algorithms for accurate range refinement of Light Detection And Ranging (LADAR) instruments. The challenges associated with wave form identification and peak-to-peak distance quantification are outlined and associated algorithms to establish peak to peak correlation between the sent and return wave forms of light are summarized. Using digital phase modulation methods, it is anticipated that some of the challenges associated with pulse digitization in LADAR range refinement algorithms can be overcome. Barker 7 and 13 codes are shown to capture the phase delay in the pulses. Implementation issues that drive the utilization of the wave form processing ideas are discussed in the context of the novel HD6D LADAR system developed by the authors. [View Full Paper]

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AAS 16-045

FAST KALMAN FILTERING FOR RELATIVE SPACECRAFT POSITION AND ATTITUDE ESTIMATION FOR THE RAVEN ISS HOSTED PAYLOAD

Joseph M. Galante,[*] John Van Eepoel,[†] Chris D'Souza[‡] and Bryan Patrick[§]

The Raven ISS Hosted Payload will feature several pose measurement sensors on a pan/tilt gimbal which will be used to autonomously track resupply vehicles as they approach and depart the International Space Station. This paper discusses the derivation of a Relative Navigation Filter (RNF) to fuse measurements from the different pose measurement sensors to produce relative position and attitude estimates. The RNF relies on relative translation and orientation kinematics and careful pose sensor modeling to eliminate dependence on orbital position information and associated orbital dynamics models. The filter state is augmented with sensor biases to provide a mechanism for the filter to estimate and mitigate the offset between the measurements from different pose sensors.

[View Full Paper]

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AAS 16-046

REUSEABLE BIRD'S-EYE VIEW FOR ON-ORBIT SATELLITE SERVICING USING CUBESATS

Christopher W. T. Roscoe,* Jason J. Westphal* and Robert T. MacMillan*

The rapid advances in small satellite technologies over the past decades have opened up a host of new opportunities for space missions. Nanosatellites and CubeSats, in particular, have grown from uncontrolled, minimally-powered university student design projects into actively-controlled, highly-agile science and surveillance platforms. Since their low mass allows them to be carried as secondary payloads on a large class of missions, these advanced CubeSats can potentially be used in a number of interesting ways to augment primary missions at little additional cost. This paper presents a mission concept—the Augmented Situational Awareness Satellite (ASAS) mission—for a reusable CubeSat to provide a bird's-eye view for an on-orbit satellite servicing mission, built on technology developed for the NASA CubeSat Proximity Operations Demonstration (CPOD) mission.

[View Full Paper]

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AAS 16-047

LABORATORY EXPERIMENTS FOR ORBITAL DEBRIS REMOVAL

Clark K. Moody,[*] Austin B. Probe,[*] Abhay Masher,[*] Timothy Woodbury,[*] Malak Saman,[†] Jeremy Davis[‡] and John E. Hurtado[§]

The orbital debris removal problem poses distinct technological challenges in sensing and autonomous control. Thorough testing of autonomous space systems is required before flight, but many ground-based facilities inadequately approximate the on-orbit environment. In this paper we describe a ground-based robotic emulation system for testing autonomous orbit debris missions and present recent experimental results. We have developed a novel active pendulum that suspends the debris target and approximates resultant contact motion. The target debris object is a reduced-scale upper-stage booster. A wheeled motion emulation robot provides six degrees of freedom for the pursuing capture vehicle and is equipped with a grappling mechanism, an inertial measurement unit, and a load cell. An autonomous guidance, navigation, and control package produces force and torque inputs into a dynamic simulation of the chaser spacecraft. The motion emulation robot follows the resultant trajectory in the laboratory space using measurements from a motion capture system as ground truth. Inputs from the load cell also feed into the chaser vehicle simulation in an effort to predict post-collision motion. Experimental data is fed real-time into a custom user interface that runs in a Web browser. Our results show the successful capture of static and spinning targets. [View Full Paper]

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ADVANCED ACCESS TO SPACE

Session 5

National Chairpersons:

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Mike Hannan, NASA Marshall Space Flight Center

Local Chairpersons:

John Abrams, Analytical Mechanics Associates, Inc.

John Reed, United Launch Alliance

Tim Bevacqua, Lockheed Martin Space Systems Company

The following papers were not available for publication:

AAS 16-051 (Paper Withdrawn)

AAS 16-053 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 16-056 to -060

AAS 16-052

VULCAN, ACES AND BEYOND: PROVIDING LAUNCH SERVICES FOR TOMORROW'S SPACECRAFT

Rich S. DeRoy[*] and John G. Reed[†]

With the announcements of new developments, partners, products and services over the last year United Launch Alliance is transforming the path to space. We will discuss many of the steps along the revolutionary path bringing the Vulcan, Advanced Common Evolved Stage (ACES) and SMART Reuse. We then delve into the enabling technologies that are being investigated. We cover the capabilities each system will bring to the market and touch on the scalability they provide. Finally we touch on the redefinition of launch service that these systems accompany and the benefits to the spacecraft GN&C community. [View Full Paper]

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AAS 16-054

ADVANCED CONTROL STRATEGY FOR EUROPEAN LAUNCHERS

Martine Ganet-Schoeller,[*] Laurent Chevalier,[†]
Jean Desmariaux[‡] and Amaya Espinosa[‡]

This paper focusses on co-founded AIRBUS DS/ASL/CNES research studies for developing advanced control strategy applicable both for launchers already in activity (with existing S/W and fixed controller structure) and for future expendable and reusable launchers. A generic framework for rapid control design is proposed here that takes advantage of all recent development in structured control design. Its application on a representative benchmark, and various applications, shows performances improvement with respect to pre-existing non structured controller, and, simplifications in control design process providing flight control development cost reduction perspectives. These results pave the way towards industrial application of structured H∞ framework for fast retuning of existing controllers and development of new controller structures for future launchers.

[View Full Paper]

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AAS 16-055

GENERALIZED PREDICTOR-CORRECTOR GUIDANCE SCHEME USED FOR A MULTI-STAGE ALL SOLID GUIDANCE STRATEGY[*]

Cary R. Maunder[†]

A Generalized Predictor-Corrector Guidance scheme was developed to guide the upper stages of the Minotaur-V launch vehicle on its mission to deliver NASA's LADEE spacecraft to the phasing orbit required for lunar insertion.[1] Minotaur V is an all-solid launch vehicle derived from the decommissioned Peacekeeper missile. The fourth stage is a Star 48 BV solid rocket motor with a vectorable nozzle for attitude control. The fifth stage is a Star 37 FM solid rocket motor with a fixed nozzle and spin stabilization. The target orbit parameters were, a perigee of 200 km, a characteristic energy of –2.75 km^2/s^2, an inclination of 37.65°, and an argument of perigee of 155°, all of which were attained with a solid spin stabilized upper stage. The insertion accuracy achieved using the guidance strategy during flight, resulted in the science portion of the LADEE mission being extended by 49 days, allowing for risky low altitude data collection that was not in the original manifest. [View Full Paper]

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MINIATURIZATION OF GUIDANCE, NAVIGATION AND CONTROL COMPONENTS

Session 6

National Chairpersons:

Andrew Shapiro,
Jet Propulsion Laboratory / California Institute of Technology

Glenn Lightsey, Georgia Institute of Technology

Local Chairpersons:

Suraj Rawal, Lockheed Martin Space Systems Company

Jim D. Chapel, Lockheed Martin Space Systems Company

The following paper numbers were not assigned:

AAS 16-066 to -070

AAS 16-061

CONCEIVE, BELIEVE AND ACHIEVE; A PATH TO MINIATURIZATION, COTS INFUSION, AND SIZE WEIGHT AND POWER REALIZATION FOR FLIGHT

Don J. Hunter,* Don F. Schatzel,† Adrian Tang,‡ Steve Fadler,§ Frank D. Egitto, Amanda Schwartz-Bowling†† and Neal Driver‡‡**

JPL along with other aerospace agencies such as the US Air Force Space Programs [A] and a packaging technology innovator, i3 Electronics, Inc., are evaluating the use of state-of-the-art (SOA) commercial off-the-shelf (COTS) and alternative packaging technologies for future high performance and high reliability space applications. Utilization of SOA COTS technologies have resulted in large scale reduction in electronics volume, weight, power, cost and schedule with outstanding electrical performance and high reliability. We will share JPL's joint design, architectural approach, alternative substrate materials selection, associated processes, and mission assurance role in identifying reliability and qualification risks, as part of the three year Heterogeneous Packaging/Device Integration effort under the guidance and leadership of JPL's Mission Assurance Directorate [B]. [View Full Paper]

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AAS 16-062

STATE OF THE ART IN GUIDANCE NAVIGATION AND CONTROL: A SURVEY OF SMALL SATELLITE GNC COMPONENTS

Roland Burton,* Sasha Weston† and Elwood Agasid‡

This paper provides a summary of current state of the art components and technologies that are used for Guidance, Navigation and Control (GNC) of small spacecraft. The current state of the art for small spacecraft GNC performance is 1.5m onboard orbital position accuracy using GPS and pointing to better than 0.1° using a combination of reaction wheels, MEMS gyros and a star tracker. Component technology for Earth orbiting missions is mature and all key GNC components are available at TRL 9 from a variety of vendors. Components for deep space small spacecraft missions are relatively immature but are expected to reach high TRL within the next two to three years. Innovation in GNC is focused on miniaturization of existing technology and the development of single vendor integrated attitude determination and control units.

This paper is based on the GNC chapter of the NASA Small Spacecraft Technology State of the Art report. [View Full Paper]

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AAS 16-063

NO LONGER TUMBLING: GNC CAPABILITIES OF TODAY'S CUBESATS

Andrew T. Klesh[*] and Aron Wolf[†]

Over the last 15 years, NanoSpacecraft have grown remarkably in capability – while early technical demonstrations utilized passive magnetic control, or tumbled freely, today's CubeSats are able to maintain 3-axis stabilization, point precisely, and even perform propulsive maneuvers. In this paper a brief discussion of current attitude determination and control capabilities is provided, as well as the possibilities for small spacecraft to maneuver. One mission taking advantage of these capabilities is MarCO (Mars Cube One), which will independently cruise to Mars in support of the InSight mission. Here we provide some description of the mission as they relate to GNC. [View Full Paper]

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AAS 16-064

REDUCING SIZE WEIGHT POWER AND COST IN STELLAR INERTIAL SPACE NAVIGATION

Bill Klein,[*] Doug Chamberlain,[†] Jean-Frederick Bouvry[‡] and Benoit Gelin[§]

This paper presents a brief history of Stellar-Inertial systems, describes the current state of the art, and discusses the approaches for reducing size, weight, and power of Stellar-Inertial systems. Design considerations for future systems, such as those targeted for the emerging small-sat applications are also presented. [View Full Paper]

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RECENT ADVANCES IN COMMERCIAL MEMORIES AND POTENTIAL CONTRIBUTION TO GN&C MINIATURIZATION*

Jean Y. Yang-Scharlotta† and Steven M. Guertin‡

The last few years have seen a surge in technology, device, and architecture introductions in commercial memories such as DRAM and NAND driven by the explosion of handheld and portable electronics. Some of the resultant devices provide high density in very small and light packages, which may be possible to leverage for the miniaturization of future GN&C systems in addition to providing considerable memory capacity to enable advanced capabilities such as image-based navigation or adaptive/autonomous operations. We will show that these advanced DRAM and NAND technologies are worth serious consideration for the next generation of GN&C needs by highlighting reliability and radiation effects results from some of these devices. [View Full Paper]

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GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)
PRECISE POSITION, NAVIGATION AND TIMING (PNT)

Session 7

National Chairpersons:

Colonel David Goldstein, U.S. Air Force

Cheryl Gramling, NASA Goddard Space Flight Center

Local Chairpersons:

Lee Barker, Lockheed Martin Space Systems Company

Mark Crews, Ball Aerospace & Technologies Corp.

The following paper numbers were not assigned:

AAS 16-079 to -080

ACHIEVING GNSS COMPATIBILITY AND INTEROPERABILITY TO SUPPORT SPACE USERS

Frank Bauer,[*] James Miller,[†] A. J. Oria[‡] and Joel Parker[§]

The development of the Global Positioning System (GPS), and other Global Navigation Satellite Systems (GNSS) such as the Russian GLONASS, the European Galileo, and China's BeiDou, is resulting in new capabilities available for Positioning, Navigation, and Timing (PNT) in orbit. This paper reviews on-going efforts to implement U.S. PNT policy and engage international partners in the pursuit of compatibility and interoperability among these systems. One of the objectives is to develop a multi-GNSS Space Service Volume (SSV) to support space users between Low Earth Orbit (LEO) and GeoSynchronous Orbit (GEO), and eventually also into Cislunar space. Key international engagements include bilateral discussions, such as those that led to the 2004 U.S.-European Union Agreement on GPS-Galileo Cooperation, and also on-going multilateral discussions at venues such the United Nations International Committee on GNSS (ICG) and GNSS Provider's Forum. Benefits to space users will include improved capabilities for on-board autonomous PNT and better resilience to potential disruptions to the signals broadcast by any one of these GNSS constellations. [View Full Paper]

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AAS 16-072

USE AND PROTECTION OF GPS SIDELOBE SIGNALS FOR ENHANCED NAVIGATION PERFORMANCE IN HIGH EARTH ORBIT

**Joel J. K. Parker,[*] Jennifer E. Valdez,[†]
Frank H. Bauer[‡] and Michael C. Moreau[*]**

The application of the Global Positioning System (GPS) for navigation of spacecraft in High and Geosynchronous Earth Orbit (HEO/GEO) has crossed a threshold and is now being employed in operational missions. Utilizing advanced GPS receivers optimized for these missions, space users have made extensive use of the sidelobe transmissions from the GPS satellites to realize navigation performance that far exceeds that predicted by pre-launch simulations. Unfortunately, the official specification for the GPS Space Service Volume (SSV), developed in 2006, assumes that only signals emanating from the main beam of the GPS transmit antenna are useful for navigation, which greatly underestimates the number of signals available for navigation purposes. As a result, future high-altitude space users may be vulnerable to any GPS design changes that suppress the sidelobe transmissions, beginning with Block III space vehicles (SVs) 11–32. This paper presents proposed changes to the GPS system SSV requirements, as informed by data from recent experiments in the SSV and new mission applications that are enabled by GPS navigation in HEO/GEO regimes. The NASA/NOAA GOESR series satellites are highlighted as an example of a mission that relies on this currently-unspecified GPS system performance to meet mission requirements. [View Full Paper]

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AAS 16-073

SOLAR FLARE DEGRADATION OF GPS NAVIGATION AT GEO

Charles J. Voboril,* Stephen F. Winkler,†
Kristin J. Larson‡ and Douglas C. Freesland§

Geosynchronous Earth Orbit (GEO) spacecraft requiring accurate position, velocity and time without ground station ephemeris uploads will rely upon Earth-pointing Global Positioning System (GPS) transmissions whose signals spill outside and beyond Earth's limb. GEO spacecraft orbiting above and outside of the GPS constellations receive signals from GPS satellites on the far side of Earth. As a consequence of GEO spacecraft antennas that must have gain extending outside Earth's disk, GEO receivers are susceptible to bursts of radio noise generated by the sun. This is an issue for the receiving GEO spacecraft during periods when Earth is between the GEO and the sun.

This study examined 25 years of historical solar flare associated radio noise data to assess signal degradation level, frequency of occurrence, and duration of events. Extensive data reduction was required to analyze 23 GB of raw data.

Spirent GPS simulator tests with the receiver hardware in the loop measured the relation between signal-to-noise (SNR) degradation and GPS output error. These tests also determined the blackout SNR level where no GPS signals are acquired or tracked.

Our work predicts that solar radio noise bursts associated with solar flares should be only a minor disruption to spacecraft using GPS for navigation and timing in steady state orbit. If a maneuver occurs during flares, then GPS error impact may be significant. Each unique mission should consider the impact of up to approximately seven separate 0.5 hour to 3 hour duration blackout periods per year. While this study focuses upon GEO spacecraft using GPS, spacecraft in other orbits as well as terrestrial GPS equipment may also be affected. [View Full Paper]

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AAS 16-074

LION NEO – A VERSATILE SPACE GNSS RECEIVER

**Peter A. Krauss, Mark Hartrampf, Andrés Barrios-Montalvo, Hannes Filippi*
and Eveline Gottzein†**

As the latest member of the LION Navigator product line, the compact LION NEO provides with its integrated LNA and its single RF front-end nevertheless the multi-frequency and multi-GNSS constellation reception capabilities of the other family members. The delivered PVT accuracy depends on scalable soft-ware modules. The LION Navigator product line is the next space qualified GNSS navigation receiver generation built by Airbus Defence and Space, developed primarily for the modernized GPS and upcoming Galileo constellation. It is software extendable to further use of other GNSS constellations, if these provide a navigation RF signal similar to GPS, e.g. GLONASS and BeiDou/COMPASS. Flight units of the LION Navigator have already been delivered to customers. [View Full Paper]

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AAS 16-075

GPS BASED NAVIGATION IMPLEMENTATION FOR GOES-R

Jeff Gillette[*] and Marco Concha[†]

The Geostationary Operational Environmental Satellites, R Series (GOES-R) will be the first GOES mission to fly a Global Positioning System (GPS) receiver (GPSR) and employ a ground based orbit determination solution that leverages the GPSR output as the primary measurement source.

The purpose of this paper is to present the GOES-R mission's ground based navigation implementation and on-orbit GPSR performance characterization scheme. The paper describes the operating phase of the GOES-R mission including orbit determination and maneuver planning concept of operations (CONOPS). The paper discusses the operational expectations for navigation performance by presenting the orbit knowledge requirements along with previously simulated and published design analysis results. This provides a framework for the discussion of how the GOES-R Mission Operations Support Team (MOST), located at the National Oceanic and Atmospheric Administration (NOAA) Satellite Operation Facility (NSOF), will characterize the GPSR's performance during three phases of the mission leading up to operations: 1) at the end of Launch and Orbit Raising (LOR) following the final Large Apogee Engine (LAE) circularization burn just below the geostationary belt, 2) during the Post Launch Test (PLT) which occurs within a dedicated geostationary slot, and 3) during relocation from the PLT geostationary slot to one of the dedicated operational geostationary slots. Also discussed is the plan to characterize and report the availability and strength of received GPS signals at geostationary orbit (GEO). [View Full Paper]

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AAS 16-076

GLOBAL POSITIONING SYSTEM NAVIGATION ABOVE 76,000 KM FOR NASA'S MAGNETOSPHERIC MULTISCALE MISSION

Luke B. Winternitz,[*] William A. Bamford,[†] Samuel R. Price,[‡] J. Russell Carpenter,[§] Anne C. Long[**] and Mitra Farahmand[††]

NASA's Magnetospheric Multiscale (MMS) mission, launched in March of 2015, consists of a controlled formation of four spin-stabilized spacecraft in similar highly elliptic orbits reaching apogee at radial distances of 12 and 25 Earth radii (RE) in the first and second phases of the mission. Navigation for MMS is achieved independently on-board each spacecraft by processing Global Positioning System (GPS) observables using NASA Goddard Space Flight Center (GSFC)'s Navigator GPS receiver and the Goddard Enhanced Onboard Navigation System (GEONS) extended Kalman filter software. To our knowledge, MMS constitutes, by far, the highest-altitude operational use of GPS to date and represents a high point of over a decade of high-altitude GPS navigation research and development at GSFC. In this paper we will briefly describe past and ongoing high-altitude GPS research efforts at NASA GSFC and elsewhere, provide details on the design of the MMS GPS navigation system, and present on-orbit performance data from the first phase. We extrapolate these results to predict performance in the second phase orbit, and conclude with a discussion of the implications of the MMS results for future high-altitude GPS navigation, which we believe to be broad and far-reaching.

[View Full Paper]

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AAS 16-077

POST-FLIGHT ANALYSIS OF GPSR PERFORMANCE DURING ORION EXPLORATION FLIGHT TEST 1*

Lee Barker,† Harvey Mamich‡ and John McGregor§

On 5 December 2014, the first test flight of the Orion Multi-Purpose Crew Vehicle executed a unique and challenging flight profile including an elevated re-entry velocity and steeper flight path angle to envelope lunar re-entry conditions. A new navigation system including a single frequency (L1) GPS receiver was evaluated for use as part of the redundant navigation system required for human space flight. The single frequency receiver was challenged by a highly dynamic flight environment including flight above low Earth orbit, as well as single frequency operation with ionospheric delay present. This paper presents a brief description of the GPS navigation system, an independent analysis of flight telemetry data, and evaluation of the GPSR performance, including evaluation of the ionospheric model employed to supplement the single frequency receiver. Lessons learned and potential improvements will be discussed. [View Full Paper]

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AAS 16-078

NAVIGATION ARCHITECTURE FOR A SPACE MOBILE NETWORK

**Jennifer E. Valdez,[*] Benjamin Ashman,[†] Cheryl Gramling,[†]
Gregory W. Heckler[‡] and J. Russell Carpenter[†]**

The Tracking and Data Relay Satellite System (TDRSS) Augmentation Service for Satellites (TASS) is a proposed beacon service to provide a global, space-based GPS augmentation service based on the NASA Global Differential GPS (GDGPS) System. The TASS signal will be tied to the GPS time system and usable as an additional ranging and Doppler radiometric source. Additionally, it will provide data vital to autonomous navigation in the near Earth regime, including space weather information, TDRS ephemerides, Earth Orientation Parameters (EOP), and forward commanding capability. TASS benefits include enhancing situational awareness, enabling increased autonomy, and providing near real-time command access for user platforms. As NASA Headquarters' Space Communication and Navigation Office (SCaN) begins to move away from a centralized network architecture and towards a Space Mobile Network (SMN) that allows for user initiated services, autonomous navigation will be a key part of such a system. This paper explores how a TASS beacon service enables the Space Mobile Networking paradigm, what a typical user platform would require, and provides an in-depth analysis of several navigation scenarios and operations concepts. [View Full Paper]

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IMAGE-BASED OPTICAL NAVIGATION

Session 8

National Chairpersons:

John Christian, West Virginia University

Brien Flewelling, Air Force Research Laboratory

Anup Katake,
Jet Propulsion Laboratory / California Institute of Technology

Local Chairpersons:

Ellis King, Charles Stark Draper Laboratory

Reuben Rohrschneider, Ball Aerospace & Technologies Corp.

The following paper numbers were not assigned:

AAS 16-089 to -090

AAS 16-081

AN EFFICIENT METHOD FOR KLT-TRACKER UNCERTAINTY QUANTIFICATION

Xue Iuan Wong* and Manoranjan Majji†

To support real time vision navigation systems and enable data driven mechanisms of ensuring consistent state estimates for relative pose estimation process, an uncertainty quantification process for the Kanade Lucas Tomasi feature tracking algorithms. It is shown that, by utilizing the high order sensitivities of the image texture about the feature location, and building upon the probabilistic models for the feature search process involving the windows, a consistent estimate of the track covariance can be computed. Although the presented framework allows for an exact propagation of the probability mass function between the search windows, the linear sensitivity analysis is used to express the covariance of the feature track. The uncertainty quantification process is shown to work effectively on simulated and real image data. Experimental images are used to also demonstrate the fact that the most uncertain features are most likely to fail to continue the tracking process. [View Full Paper]

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AAS 16-082

VISION NAVIGATION PERFORMANCE FOR AUTONOMOUS ORBITAL RENDEZVOUS AND DOCKING

Eric Dahlin,[*] David Woffinden[†] and Pol Spanos[‡]

This research effort demonstrates the potential of performing orbital rendezvous and docking using vision navigation. The vision navigation algorithm tracks both known and unknown target features to determine the relative position and attitude between a chaser and target spacecraft. By processing imagery generated from an optical sensor, various target features can be tracked to accurately determine the relative motion between two orbiting vehicles. An architecture is adopted that uses an extended Kalman filter (EKF) to processes angle measurements to various target features as extracted from the vision navigation algorithm. A Monte Carlo simulation is used to assess the performance of the navigation filter in a closed-loop guidance, navigation, and control (GNC) system. This paper introduces strategies to overcome the resulting range dilemma and characterizes the performance of using vision navigation for autonomous orbital rendezvous and docking.

[View Full Paper]

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AAS 16-083

NEW HORIZONS OPTICAL NAVIGATION ON APPROACH TO PLUTO

Coralie D. Jackman,[*] Derek S. Nelson,[†] William M. Owen, Jr.,[‡] Marc W. Buie,[§] S. Alan Stern,[§] Harold A. Weaver,[**] Leslie A. Young,[§] Kimberly Ennico[††] and Catherine B. Olkin[§]

The navigation of the New Horizons spacecraft on approach to Pluto has required an extensive set of data products, including those derived from optical observation. Due to the relatively large *a priori* uncertainties of the spacecraft ephemeris with respect to the Pluto system, optical navigation has played a critical role in decreasing the body-relative errors and enabling a successful flyby. Key functions of the New Horizons optical navigation process include extensive image planning and processing, stellar and planetary modeling, attitude determination, and star and planetary body centroiding. This paper presents how these functions enabled the successful navigation of New Horizons' flyby of the Pluto system. [View Full Paper]

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AAS 16-084

RELATIVE TERRAIN IMAGING NAVIGATION (RETINA) TOOL FOR THE ASTEROID REDIRECT ROBOTIC MISSION (ARRM)

Cinnamon A. Wright,* John Van Eepoel,† Andrew Liounis,‡ Michael Shoemaker,§ Keith DeWeese† and Kenneth Getzandanner*

As a part of the NASA initiative to collect a boulder off of an asteroid and return it to Lunar orbit, the Satellite Servicing Capabilities Office (SSCO) and NASA GSFC are developing an on-board relative terrain imaging navigation algorithm for the Asteroid Redirect Robotic Mission (ARRM). After performing several flybys and dry runs to verify and refine the shape, spin, and gravity models and obtain centimeter level imagery, the spacecraft will descend to the surface of the asteroid to capture a boulder and return it to Lunar Orbit. The algorithm implements Stereophotoclinometry methods to register landmarks with images taken onboard the spacecraft, and use these measurements to estimate the position and orientation of the spacecraft with respect to the asteroid. This paper will present an overview of the ARRM GN&C system and concept of operations as well as a description of the algorithm and its implementation. These techniques will be demonstrated for the descent to the surface of the proposed asteroid of interest, 2008 EV5, and preliminary results will be shown. [View Full Paper]

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DEVELOPMENT AND FLIGHT OF A STEREOSCOPIC IMAGER FOR USE IN SPACECRAFT CLOSE PROXIMITY OPERATIONS

Jacob E. Darling,[*] Keith A. LeGrand,[*] Pavel Galchenko,[*] Henry J. Pernicka,[†] Kyle J. DeMars,[‡] Alexander T. Shirley,[§] James S. McCabe,[*] Christine L. Schmid,[*] Samuel J. Haberberger[*] and Alex J. Mundahl[**]

Proximity operations about noncooperative resident space objects (RSOs) is a current area of research with the intent to enable many useful on-orbit missions. One method of performing passive proximity operations about a noncooperative RSO uses two cameras to obtain stereo line-of-sight data to the RSO in order to fully resolve the relative position and velocity of the RSO and navigate about it. An overview of the MR and MRS SAT mission, in which a stereoscopic imager is used aboard MR SAT to navigate about MRS SAT (a mock noncooperative RSO) is presented. The developed hardware and algorithms used by the stereoscopic imaging sensor, as well as the guidance, navigation, and control subsystems, are presented. A software-in-the-loop simulation is presented to demonstrate the expected on-orbit performance of the MR and MRS SAT mission. [View Full Paper]

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AAS 16-086

OSIRIS-REX ASTEROID SAMPLE COLLECTION—OPEN-LOOP TESTING OF OPTICAL-BASED FEATURE TRACKING AT THE SPACE OPERATIONS SIMULATION CENTER (SOSC)

Reid W. Hamilton,[*] Chris Norman[†] and David Huish[‡]

OSIRIS-REx (**O**rigins, **S**pectral **I**nterpretation, **R**esource **I**dentification, **S**ecurity, **R**egolith **Ex**plorer) is a NASA Goddard Space Flight Center (GSFC) asteroid sample and return mission that will return asteroid gravel and dust to the Earth. With an optical navigation camera called NavCam, it employs Natural Feature Tracking (NFT) to navigate near the asteroid surface. To test NFT, images of an asteroid model were collected from the expected spacecraft trajectory using the large 6-DOF (degrees of freedom) robot at the Space Operations Simulation Center (SOSC) located at the Lockheed Martin Space Systems Company, Denver Waterton campus.

OSIRIS-REx is flying to Bennu, an asteroid with a diameter of approximately 500 m. This test began by building a 14x14.5-meter model of a region of the asteroid near the touch and go (TAG) site. This model stands as a large wall. The wall was scanned with a Lidar and the resulting point cloud was converted into a digital elevation map (DEM). From the DEM, a catalog of target features was created that NFT uses to estimate the spacecraft state over the trajectory from 55 meters to 20 meters. The flight dynamics were supplied by NASA, and the OSIRIS-REx NavCam Engineering Development Unit (EDU) was used to collect images. The trajectories were ran as open-loop approaches and NFT was tested offline by passing these images into the NFT simulation of the OSIRIS-REx approach.

In a previous paper, we outlined the OSIRIS-REx approach to NFT[1]. In this paper, we report on SOSC testing and lessons learned. [View Full Paper]

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ROBUSTNESS AND PERFORMANCE IMPACTS OF OPTICAL-BASED FEATURE TRACKING TO OSIRIS-REX ASTEROID SAMPLE COLLECTION MISSION*

Courtney Mario† and Chris Debrunner‡

The OSIRIS-REx (Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer) mission is designed to collect and return a sample of regolith from the asteroid Bennu. Natural Feature Tracking (NFT) is an optical-based feature tracking subsystem currently being developed to assist with this sample collection by autonomously providing orbit state updates. NFT uses a catalog of known features built from an asteroid shape model that is produced during flight as more information about Bennu is collected. During the sample collection phase of the mission, these features are rendered using a predicted camera pose and sun position, and correlated against real-time images of the asteroid surface. The results of this correlation are then used to provide a state update of the spacecraft's position and velocity relative to the asteroid surface.

The design of the feature catalog used by NFT is critical to NFT's performance. In addition to making sure that the asteroid surface has adequate feature coverage, each feature must contain data that can be reliably rendered and correlated in flight. Shape model errors will impact the knowledge of the true feature position and shape, and therefore impact how a feature is rendered. Other factors such as lighting variations and unknown asteroid surface conditions can also impact correlation performance.

This paper will explore how shape model errors, feature data resolution, lighting conditions, and other factors can impact correlation performance, both in pixel error and by also introducing false correlation peaks. Results will be generated using both simulated images of the asteroid, as well as images collected with the asteroid wall mock-up in the Space Operations Simulation Center (SOSC), at the Lockheed Martin Denver Waterton campus. Ultimately, this paper will explore how these correlation errors impact the overall performance of NFT. [View Full Paper]

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AAS 16-088

ASTRO APS STAR TRACKER PERFORMANCE ON SENTINEL-2A

Uwe Schmidt,[*] Boris Pradarutti,[†] Juergen Mehlhorn,[‡] Ingolf Steinbach[§] and Axel Kwiatkowski[**]

The ASTRO APS star tracker is an autonomous 3-axis attitude measurement sensor being currently the state of the art ASTRO-series star tracker product of Jena-Optronik GmbH/Germany. On board of the Sentinel-2A spacecraft, specifically designed by Airbus Defence & Space as prime contractor for the operational needs of the Copernicus program, 3 ASTRO APS star trackers have been launched on the 23rd of June 2015. Sentinel-2A is a 3-axis stabilized Earth observation spacecraft operating on a 716.42km near polar frozen Sun-synchronous orbit with 98.62deg inclination. The project team of Jena-Optronik GmbH received from Airbus DS a comprehensive data package in order to characterize the star tracker performance under the typical environmental conditions of a low Earth orbit. The in-orbit data contain the temperature telemetry, the 3-axes attitude quaternions and angular rate measurements. These data are complete for 3 orbits with 10Hz star tracker sampling rate and are fully synchronous for the two operational star trackers. This allows reducing the superimposed spacecraft motion dynamic from the star tracker quaternion data, getting finally the isolated single star tracker total attitude random error which contains the temporal error and the high-/low spatial frequency noise budgets. With these on-orbit data evaluations it could be shown that the ASTRO APS star trackers on Sentinel-2A operate within the specification limits under the challenging radiative thermal control environment. This paper summarizes the most interesting results of the Sentinel-2A star tracker data evaluation with the corresponding discussions and assessments. [View Full Paper]

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PIONEERS IN GUIDANCE, NAVIGATION, CONTROL AND ASTRONAUTICS

Session 9

National Chairperson:

Louis Herman, The Aerospace Corporation

Local Chairpersons:

James McQuerry, Ball Aerospace & Technologies Corp. (retired)

Larry Germann, Left Hand Design Corp.

The following paper was not available for publication:

AAS 16-094 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 16-096 to -100

AAS 16-091

GUIDANCE DEVELOPMENTS OF ROBERT GODDARD AND THE GERMANS AT PEENEMÜNDE

John L. Goodman*

Dr. Robert Goddard performed the first successful flight demonstration of gyroscopically controlled vertical rocket flight on March 28, 1935 near Roswell, New Mexico. German Army research into missile guidance started in the early 1930s and resulted in the LEV-3 system that was flown on the V-2 (A-4) during World War II. The LEV-3 and other developments at Peenemünde led directly to guidance systems developed in Huntsville, Alabama for the Redstone, Jupiter, Pershing I, and Saturn vehicles. [View Full Paper]

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AAS 16-092

ADVANCES IN GUIDANCE, NAVIGATION, AND CONTROL FOR PLANETARY ENTRY, DESCENT, AND LANDING SYSTEMS

Zachary R. Putnam[*] and Robert D. Braun[†]

Planetary entry, descent, and landing has been performed successfully at Venus, Earth, Mars, Jupiter, Titan, and the moon, producing a wealth of *in situ* data not available from in-space remote-sensing platforms. To achieve such success, entry, descent, and landing systems have been designed to accommodate a wide variety of mission scenarios and environments, from the thin atmosphere of Mars to the thick atmosphere of Venus, from atmospheric entry velocities as low as 4 km/s at Mars to nearly 48 km/s at Jupiter. The history and development of the complex systems necessary to successfully execute entry, descent, and landing is summarized and discussed, with a focus on guidance and control strategies. Improvements to inertial navigation systems and interplanetary approach navigation techniques are highlighted. Mission requirements that drive entry, descent, and landing system design are identified. Lastly, future challenges and goals for entry, descent, and landing systems are enumerated and current technology development efforts are discussed. [View Full Paper]

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AAS 16-093

POWERED GUIDANCE DEVELOPMENT FOR APOLLO AND THE SPACE SHUTTLE

John L. Goodman*

The 1950s era reference trajectory and correlated guidance techniques (Delta Minimum, Delta, and Q) were not capable of supporting space missions envisioned by 1960. The development of digital flight computers enabled explicit guidance algorithms to be developed using results from the calculus of variations. The Iterative Guidance Mode (IGM) and E Guidance were explicit guidance schemes that were successfully developed for and flown in the Apollo Program. Hypersurface targeting provided constraints to IGM for the Trans Lunar Injection burn. Powered Explicit Guidance (PEG) was developed later and successfully flew on the Space Shuttle from 1981 to 2011. PEG was a more capable algorithm that could support demanding Space Shuttle abort profiles.

[View Full Paper]

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A SHORT HISTORY OF THE SPACE SHUTTLE ORBIT FLIGHT CONTROL SYSTEM DEVELOPMENT AND APPLICATION EVOLUTION*

Philip D. Hattis[1]

The Space Shuttle Orbit Flight Control System (OFCS) provided all Guidance, Navigation, and Control capabilities from external tank separation during ascent until entry interface during return. Its development began in earnest in 1975 with first orbital flight application in 1981. The many operational requirements for the Shuttle and its unique vehicle design characteristics demanded specialized algorithms and numerous functional features despite very limited computer memory and speed by contemporary standards. This paper provides a short history of the Shuttle OFCS development and orbital application evolution. [View Full Paper]

[2]

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[2] From http://www.spaceline.org/rocketsum/shuttle-program.html.

SMALL BODY ENCOUNTERS

Session 10

National Chairpersons:

Mike Moreau, NASA Goddard Space Flight Center

Dante Lauretta, University of Arizona

Local Chairpersons:

Dan Kubitschek, University of Colorado at Boulder LASP

Lisa Hardaway, Ball Aerospace & Technologies Corp.

The following paper numbers were not assigned:

AAS 16-108 to -110

AAS 16-101

OSIRIS-REX ORBIT DETERMINATION COVARIANCE STUDIES AT BENNU

P. G. Antreasian,[*] M. Moreau,[†] C. Jackman,[*] K. Williams,[*] B. Page[*] and J. M. Leonard[*]

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 small, Earth-crossing asteroid (101955) Bennu in late 2018, ultimately returning a sample of regolith to Earth. Approximately three months before the encounter with Bennu, the asteroid becomes detectable in the narrow field PolyCam imager. The spacecraft's rendezvous with Bennu begins with a series of four Asteroid Approach Maneuvers, slowing the spacecraft's speed relative to Bennu beginning two and a half months prior to closest approach, ultimately delivering the spacecraft to a point 18 km from Bennu in Nov, 2018. An extensive campaign of proximity operations activities to characterize the properties of Bennu and select a suitable sample site will follow. This paper will discuss the challenges of navigating near a small 500-m diameter asteroid. The navigation at close proximity is dependent on the accurate mathematical model or digital terrain map of the asteroid's shape. Predictions of the spacecraft state are very sensitive to spacecraft small forces, solar radiation pressure, and mis-modeling of Bennu's gravity field. Uncertainties in the physical parameters of the central body Bennu create additional challenges. The navigation errors are discussed and their impact on science planning will be presented. [View Full Paper]

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AAS 16-102

GUIDANCE AND OPTICAL NAVIGATION FOR SMALL BODY DESCENT TRAJECTORIES

Brenton Duffy,* Timothy McGee* and Antonio Diaz-Calderon*

This paper overviews recent development of flight software and testbed simulation for autonomous guidance, navigation, and control (GN&C) relative to small planetary bodies. Previous missions experienced complications due to high degrees of uncertainty in the body shape and gravity field, significant perturbations arising from solar effects and body out-gassing, and varying degrees of reliability for on board sensors at varying altitudes. Strategies are presented for mitigation against these challenges within the design of a practical, flight-level GN&C system incorporating passive optical terrain relative navigation. Simulation results are included for a descent and landing onto comet 67P/CG.

[View Full Paper]

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AAS 16-103

AN INDEPENDENT ORBIT DETERMINATION SIMULATION FOR THE OSIRIS-REX ASTEROID SAMPLE RETURN MISSION

Kenneth Getzandanner,[*] David Rowlands,[†] Erwan Mazarico,[†] Peter Antreasian,[‡] Coralie Jackman[§] and Michael Moreau[**]

After arriving at the near-Earth asteroid (101955) Bennu in late 2018, the OSIRIS-Rex spacecraft will execute a series of observation campaigns and orbit phases to accurately characterize Bennu and ultimately collect a sample of pristine regolith from its surface. While in the vicinity of Bennu, the OSIRIS-REx navigation team will rely on a combination of ground-based radiometric tracking data and optical navigation (OpNav) images to generate and deliver precision orbit determination products. Long before arrival at Bennu, the navigation team is performing multiple orbit determination simulations and thread tests to verify navigation performance and ensure interfaces between multiple software suites function properly. In this paper, we summarize the results of an independent orbit determination simulation of the Orbit B phase of the mission performed to test the interface between the OpNav image processing and orbit determination software packages.

[View Full Paper]

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AAS 16-104

SURFACE PROXIMITY GRAVITATIONAL FIELD ANALYSIS OF THE ASTEROID 433 EROS

Siamak G. Hesar,* Daniel J. Scheeres,† Jay W. McMahon‡ and Yu Takahashi§

Regular spherical harmonics representation of the gravitational field of an object is not accurate within a circumscribing sphere of the body of mass, called the Brillouin sphere. This is a major issue in modeling the gravitational field of asteroids and comets with significant non-spherical shapes, as certain regions in the close proximity of the surface of such objects fall well within the Brillouin sphere. We implement a so called "interior" spherical harmonics expansion to model the surface proximity gravitational field of the asteroid 433 Eros. This model is shown to be able to accurately represent the gravitational field of an object in the close proximity of its surface. However, estimating the coefficients of such model is challenging. This work studies the feasibility of estimating the coefficients of an interior gravity field via orbit determination. The paper presents the expected level of the estimation precision and characterizes the effect of the size of the field radius on the estimation performance. [View Full Paper]

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AAS 16-105

ASTEROID REDIRECT MISSION PROXIMITY OPERATIONS FOR REFERENCE TARGET ASTEROID 2008 EV_5

David M. Reeves,[*] Daniel D. Mazanek,[†] Ben D. Cichy,[‡]
Stephen B. Broschart[§] and Keith D. DeWeese[**]

NASA's Asteroid Redirect Mission (ARM) is composed of two segments, the Asteroid Redirect Robotic Mission (ARRM), and the Asteroid Redirect Crewed Mission (ARCM). In March of 2015, NASA selected the Robotic Boulder Capture Option[1] as the baseline for the ARRM. This option will capture a multi-ton boulder, (typically 2-4 meters in size) from the surface of a large (greater than ~100 m diameter) Near-Earth Asteroid (NEA) and return it to cis-lunar space for subsequent human exploration during the ARCM. Further human and robotic missions to the asteroidal material would also be facilitated by its return to cis-lunar space. In addition, prior to departing the asteroid, the Asteroid Redirect Vehicle (ARV) will perform a demonstration of the Enhanced Gravity Tractor (EGT) planetary defense technique.[2] This paper will discuss the proximity operations which have been broken into three phases: Approach and Characterization, Boulder Capture, and Planetary Defense Demonstration. Each of these phases has been analyzed for the ARRM reference target, 2008 EV_5, and a detailed baseline operations concept has been developed. [View Full Paper]

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AAS 16-106

GN&C OF HAYABUSA2 IN "CRUISING PHASE" AND "ASTEROID PROXIMITY PHASE"

Fuyuto Terui,[*] Naoko Ogawa,[†] Yuya Mimasu,[‡] Go Ono,[§] Satoshi Ueda,[**] Toru Yamamoto,[§] Tomohiro Yamaguchi,[‡] Takanao Saiki[††] and Yuichi Tsuda[‡‡]

A new asteroid exploration spacecraft "Hayabusa2" as a follow on of "Hayabusa" was launched on 3rd of December 2014 from Tanegashima Space Center located in the south part of Japan. The planned missions of Hayabusa2 are round trip to the target asteroid "Ryugu", scientific observation of the asteroid, releasing small rover and lander to the surface of the asteroid for scientific and engineering purposes, releasing explosive called "Small Carry on Impactor" to the asteroid in order to make a crater on the surface of the asteroid and multiple times of touchdown including "pinpoint touchdown" toward the newly created crater in order to get "fresh" material underneath the surface of it. This paper show the recent result of operation in "cruising phase" such as Earth swing-by successfully conducted in December 2015. Then current status of detailed analysis for "Asteroid Proximity Phase" is provided such as the entire planning for proximity operation, global mapping and trajectory analysis for approach to the asteroid which could be essential for successful operations in this phase. [View Full Paper]

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AAS 16-107

DETERMINATION OF CERES PHYSICAL PARAMETERS USING RADIOMETRIC AND OPTICAL DATA

Brian M. Kennedy, Nicholas Bradley, Dongsuk Han, Reza Karimi, Nickolaos Mastrodemos, Brian Rush and Yu Takahashi*

The Dawn spacecraft was launched on September 27th, 2007. Its mission is to rendezvous with and observe the two largest bodies in the main asteroid belt, Vesta and Ceres. It has completed over a year's worth of direct observations of Vesta from early 2011 through late 2012. In the spring of 2015, the Dawn spacecraft entered orbit around the asteroid Ceres for the start of what is expected to be more than a year of science operations. The science data collected from this encounter consist of infrared (IR) images and spectra, visible images through a number of color filters, gamma ray detections and measurements of the Ceres gravity field. These data will be collected during several science phases: an Approach phase (1500000-4860 km from Ceres), a Survey orbit (4860 km radius), a High Altitude Mapping Orbit (HAMO) (1940 km radius) and a Low Altitude Mapping Orbit (LAMO) (855 km radius). The Approach phase included three Rotational Characterization (RC) opportunities. [View Full Paper]

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ORION SPECIAL SESSION

Session 11

National Chairpersons:

Tim Straube, NASA Johnson Space Center

Jack Brazzel, NASA Johnson Space Center

Local Chairpersons:

Mike Begley, Lockheed Martin Space Systems Company

John Bendle, Lockheed Martin Space Systems Company

The following paper numbers were not assigned:

AAS 16-118 to -120

AAS 16-111

EVOLUTION OF ORION MISSION DESIGN FOR EXPLORATION MISSION 1 AND 2

Jeffrey P. Gutkowski,* Timothy F. Dawn* and Richard M. Jedrey*

The evolving mission design and concepts of NASA's next steps have shaped Orion into the spacecraft that it is today. Since the initial inception of Orion, through the Constellation Program, and now in the Exploration Mission frame-work with the Space Launch System (SLS), each mission design concept and pro-gram goal have left Orion with a set of capabilities that can be utilized in many different mission types. Exploration Missions 1 and 2 (EM-1 and EM-2) have now been at the forefront of the mission design focus for the last several years. During that time, different Design Reference Missions (DRMs) were built, analyzed, and modified to solve or mitigate enterprise level design trades to ensure a viable mission from launch to landing. The resulting DRMs for EM-1 and EM-2 were then expanded into multi-year trajectory scans to characterize vehicle performance as affected by variations in Earth-Moon geometry. This provides Orion's subsystems with stressing reference trajectories to help design their system. Now that Orion has progressed through the Preliminary and Critical Design Reviews (PDR and CDR), there is a general shift in the focus of mission design from aiding the vehicle design to providing mission specific products needed for pre-flight and real time operations. Some of the mission specific products needed include, large quantities of nominal trajectories for multiple monthly launch periods and abort options at any point in the mission for each valid trajectory in the launch window. [View Full Paper]

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AAS 16-112

ENCKE-BETA PREDICTOR FOR ORION BURN TARGETING AND GUIDANCE

Shane Robinson,[*] Sara Scarritt[*] and John L. Goodman[†]

The state vector prediction algorithm selected for Orion on-board targeting and guidance is known as the Encke-Beta method. Encke-Beta uses a universal anomaly (beta) as the independent variable, valid for circular, elliptical, parabolic, and hyperbolic orbits. The variable, related to the change in eccentric anomaly, results in integration steps that cover smaller arcs of the trajectory at or near perigee, when velocity is higher. Some burns in the EM-1 and EM-2 mission plans are much longer than burns executed with the Apollo and Space Shuttle vehicles. Burn length, as well as hyperbolic trajectories, has driven the use of the Encke-Beta numerical predictor by the predictor/corrector guidance algorithm in place of legacy analytic thrust and gravity integrals. [View Full Paper]

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[‡] Encke's method was developed at least 56 years before Cowell published his method in 1908. [4]

AAS 16-113

ORION BURN MANAGEMENT, NOMINAL AND RESPONSE TO FAILURES

Ryan Odegard,[*] John L. Goodman,[†] Charles P. Barrett,[‡] Kara Pohlkamp[§] and Shane Robinson[**]

An approach for managing Orion on-orbit burn execution is described for nominal and failure response scenarios. The burn management strategy for Orion takes into account per-burn variations in targeting, timing, and execution; crew and ground operator intervention and overrides; defined burn failure triggers and responses; and corresponding on-board software sequencing functionality. Burn-to-burn variations are managed through the identification of specific parameters that may be updated for each progressive burn. Failure triggers and automatic responses during the burn timeframe are defined to provide safety for the crew in the case of vehicle failures, along with override capabilities to ensure operational control of the vehicle. On-board sequencing software provides the timeline coordination for performing the required activities related to targeting, burn execution, and responding to burn failures. [View Full Paper]

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AAS 16-114

ORION GN&C DETECTION AND MITIGATION OF PARACHUTE PENDULOSITY

Mark A. Kane*[*] and Roger Wacker[†]

New techniques being employed by Orion guidance, navigation, and control (GN&C) using a reaction control system (RCS) under parachutes are described. Pendulosity refers to a pendulum-oscillatory mode that can occur during descent under main parachutes and that has been observed during Orion parachute drop tests. The pendulum mode reduces the ability of GN&C to maneuver the suspended vehicle resulting in undesirable increases to structural loads at touchdown. Parachute redesign efforts have been unsuccessful in reducing the pendulous behavior necessitating GN&C mitigation options. An observer has been developed to estimate the pendulum motion as well as the underlying wind velocity vector. Using this knowledge, the control system maneuvers the vehicle using two separate strategies determined by wind velocity magnitude and pendulum energy thresholds; at high wind velocities the vehicle is aligned with the wind direction and for cases with lower wind velocities and large pendulum amplitudes the vehicle is aligned such that it is perpendicular to the swing plane. Pendulum damping techniques using RCS thrusters are discussed but have not been selected for use onboard the Orion spacecraft. The observer and alignment techniques discussed in this paper will be flown on Exploration Mission 1 (EM-1). [View Full Paper]

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AAS 16-115

ORION GN&C FAULT MANAGEMENT SYSTEM VERIFICATION: SCOPE AND METHODOLOGY

Denise Brown,[*] David Weiler[†] and Ronald Flanary[‡]

In order to ensure long-term ability to meet mission goals and to provide for the safety of the public, ground personnel, and any crew members, nearly all spacecraft include a fault management (FM) system. For a manned vehicle such as Orion, the safety of the crew is of paramount importance. The goal of the Orion Guidance, Navigation and Control (GN&C) fault management system is to detect, isolate, and respond to faults before they can result in harm to the human crew or loss of the spacecraft. Verification of fault management/fault protection capability is challenging due to the large number of possible faults in a complex spacecraft, the inherent unpredictability of faults, the complexity of interactions among the various spacecraft components, and the inability to easily quantify human reactions to failure scenarios. The Orion GN&C Fault Detection, Isolation, and Recovery (FDIR) team has developed a methodology for bounding the scope of FM system verification while ensuring sufficient coverage of the failure space and providing high confidence that the fault management system meets all safety requirements. The methodology utilizes a swarm search algorithm to identify failure cases that can result in catastrophic loss of the crew or the vehicle and rare event sequential Monte Carlo to verify safety and FDIR performance requirements. [View Full Paper]

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AAS 16-116

GEOMETRIC CALIBRATION OF THE ORION OPTICAL NAVIGATION CAMERA USING STAR FIELD IMAGES

John A. Christian,* Lylia Benhacine† and Jacob Hikes†

The Orion Multi Purpose Crew Vehicle will be capable of autonomously navigating in cislunar space using images of the Earth and Moon. Optical navigation systems, such as the one proposed for Orion, require the ability to precisely relate the observed location of an object in a 2D digital image with the true corresponding line-of-sight direction in the camera's sensor frame. This relationship is governed by the camera's geometric calibration parameters — typically described by a set of five intrinsic parameters and five lens distortion parameters. While pre-flight estimations of these parameters will exist, environmental conditions often necessitate on-orbit recalibration. This calibration will be performed for Orion using an ensemble of star field images. This manuscript provides a detailed treatment of the theory and mathematics that will form the foundation of Orion's on-orbit camera calibration. Numerical results and examples are also presented.

[View Full Paper]

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AAS 16-117

ORION EXPLORATION FLIGHT TEST 1 (EFT-1) BEST ESTIMATED TRAJECTORY DEVELOPMENT

Greg N. Holt* and Aaron Brown†

The Orion Exploration Flight Test 1 (EFT-1) mission successfully flew on Dec 5, 2014 atop a Delta IV Heavy launch vehicle. The goal of Orion's maiden flight was to stress the system by placing an uncrewed vehicle on a high-energy trajectory replicating conditions similar to those that would be experienced when returning from an asteroid or a lunar mission. The Orion navigation team combined all trajectory data from the mission into a Best Estimated Trajectory (BET) product. There were significant challenges in data reconstruction and many lessons were learned for future missions. The team used an estimation filter incorporating radar tracking, onboard sensors (Global Positioning System and Inertial Measurement Unit), and day-of-flight weather balloons to evaluate the true trajectory flown by Orion. Data was published for the entire Orion EFT-1 flight, plus objects jettisoned during entry such as the Forward Bay Cover. The BET customers include approximately 20 disciplines within Orion who will use the information for evaluating vehicle performance and influencing future design decisions. [View Full Paper]

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IN SPACE
PROPULSION INNOVATIONS

Session 12

National Chairperson:

Jeff Sheehy, NASA Headquarters

Local Chairpersons:

Bryce Unruh, Ball Aerospace & Technologies Corp.

Christopher McLean, Ball Aerospace & Technologies Corp.

Jeff Parker, University of Colorado at Boulder

The following papers were not available for publication:

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AAS 16-123 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 16-129 to -130

AAS 16-121

GREEN PROPELLANT INFUSION MISSION: PROGRAM OVERVIEW AND STATUS

Christopher H. McLean[*]

The NASA Space Technology Mission Directorate's (STMD) Green Propellant Infusion Mission (GPIM) Technology Demonstration Mission (TDM) is comprised of a cross-cutting team of domestic spacecraft propulsion and storable green propellant technology experts. This TDM is led by Ball Aerospace & Technologies Corp. (BATC), who will use their BCP-100 spacecraft as a platform for a green propellant propulsion payload that includes five 1 N thrusters. These thrusters will be used for attitude control and Delta-V maneuvers during a 13 month flight demonstration. The GPIM project has technology infusion-team members from all three major market sectors: Industry, NASA, and the Department of Defense (DoD). The GPIM project team includes BATC, Aerojet Rocketdyne (AR), Air Force Research Laboratory, Edwards Air Force Research Laboratory (AFRL), NASA Glenn Research Center (GRC), NASA Kennedy Space Center (KSC), and NASA Goddard Space Flight Center (GSFC). STMD programmatic and technology oversight is provided by NASA Marshall Space Flight Center (MSFC). This paper also provides an overview of four secondary payloads being matured by Ball and its partners. Currently the GPIM space vehicle is completed, including the integration of the propulsion subsystem and secondary payloads with a launch slated for September 2016 aboard Space-X's Falcon 2 Heavy for the Air Force's STP-2 mission. At the completion of a 13 month on-orbit demonstration, sufficient data will be developed to allow for infusion of AFM315E as a hydrazine replacement for spacecraft attitude control and primary propulsion. A successful demonstration will bring this technology to TRL 7+. Subsequent infusion of this green propellant based thrusters are expected to result in lower cost, increased safety and higher performance as compare to thrusters of this class currently used by the spacecraft industry. [View Full Paper]

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AAS 16-124

SCALABLE IONIC LIQUID ELECTROSPRAY THRUSTERS FOR NANOSATELLITES

David Krejci[*] and Paulo Lozano[†]

While the number of Nanosatellites launched has rising rapidly in recent years, this satellite class still suffers from a lack of high efficient, reasonable miniaturized propulsion systems. The Space Propulsion Laboratory at MIT has therefore developed a miniaturized electrostatic thruster technology based on Microelectromechanical systems (MEMS) manufacturing processes. This electrospray thruster consists of an array of 480 ion emitter tips per square centimeter and uses room temperature molten salts as propellant, achieving a specific impulse of >1150s with an approximate thrust density of 12μN/cm^2. Multiple of these thrusters can be added together in a modular way. A propulsion module featuring 8 of these thrusters has been developed under the NASA Microfluidic Electrospray Propulsion (MEP) program, delivering primary propulsion to Cubesats for orbit correction and change maneuvers. Including power processing unit (PPU), this propulsion module fits in a 0.2U envelope, weighting less than 100g. A thrust of 74μN was measured for this unit at a total power consumption of 1.5-2W, complying with Cubesats as small as 1.5U. In addition, the modular nature of the thruster allows easy up scaling of the propulsion unit up to 36 thrusters per Cubesat panel, leading to a projected Δv in the order of 1km/s for a 3U Cubesat. [View Full Paper]

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AAS 16-125

CONSIDERATIONS FOR OPERATION OF A DEEP SPACE NANOSATELLITE PROPULSION SYSTEM

Matt Sorgenfrei,[*] Terry Stevenson[†] and E. Glenn Lightsey[‡]

A distinguishing feature of deep space CubeSats is that they require some form of propulsion system, either for orbital maneuvering operations, spacecraft momentum management, or both. However, the comparatively short lifecycle for these missions, combined with the mass and volume restrictions that are attendant with the CubeSat form factor, make the integration of propulsion systems one of the highest-risk aspects of the entire mission. There are a limited number of facilities around the country that can support accurate testing of thruster systems that generate milli-Newtons of thrust, and the cost associated with handling and transportation of traditional propellants can be prohibitive for many CubeSat mission budgets. As a result, many deep space CubeSats are considering propulsion systems that are either at a fairly low technology readiness level or which will be integrated after a truncated test campaign. This paper will describe the propulsion system architecture selected for the BioSentinel mission, a six-unit CubeSat under development at NASA Ames Research Center. BioSentinel requires a propulsion system to support detumble and momentum management operations, and this paper will discuss the integration of a third-party propulsion system with an Ames-built CubeSat, as well as the test campaign that is underway for both quality control and requirements verification purposes. [View Full Paper]

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ASSESSING AND TAKING UP THE CHALLENGES TO AN EPBASED SPACE TUG FOR ON-ORBIT COMMERCIAL SERVICING

Guillaume Pionnier,[*] Julien Doinet[*] and Pierre-Nicolas Gineste[†]

Based on its long experience on geostationary satellites and thanks to its new GEO electrical platform Neosat, Airbus Defence and Space well-masters the Electrical Orbit Raising and long station keeping phase issues already. However, within the developments of a foreseen electrical spacecraft for on-orbit servicing operations, one of the most critical GN&C challenges to be addressed is to perform a rendezvous based on a highly power demanding, low thrust and quasi-continuous propulsion system, with a semi- to non-cooperative target. Through this paper, Airbus DS proposes a solution to solve this multiple constrained problem, in once. [View Full Paper]

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AAS 16-127

GN&C APPLICATIONS USING NEXT GENERATION NEXT-C HIGH POWER ION THRUSTER

Steven Overton,[*] Jerry Jackson,[†] Ronald Spores,[‡] Kevin Kelleher,[§] May Allen,[**] Thomas Hertel[††] and Andy Hoskins[‡‡]

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Aerojet Rocketdyne (AR) is currently under contract to NASA Glenn Research Center for the development of the NEXT-C (NASA Evolutionary Xenon Thruster – Commercial) electric propulsion system. The 7kW NEXT-Commercial variant is based on the flight demonstrated history of the NSTAR (NASA Solar Technology Application Readiness) thruster and significant life testing of the original NEXT thruster. In addition to developing the NEXT-C thruster for potential future NASA Discovery Missions, AR is dedicated to ensuring that the propulsion system is viable for commercial uses and applications. When the contract is complete, NEXT-C will be the highest power ion engine qualified to date. The new NEXT-C thruster presents GN&C engineers and spacecraft developers with significant new capabilities and benefits that can be leveraged on upcoming NASA Discovery and New Frontiers missions as well as commercial applications. There are a number of unique applications that can benefit from the new thruster such as missions to planets and bodies with a wide range of gravitational fields, missions requiring extended/continuous varying thrusting operations and extremely long life and high delta-V missions requiring highly efficient propulsion for attitude control and main propulsion operation. This paper provides insight into the AR development activities, the roadmap to commercial infusion and evolution, and potential applications using the NEXT-C propulsion system. [View Full Paper]

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AAS 16-128

STRATEGIC TECHNOLOGIES FOR DEEP SPACE TRANSPORT

Ronald J. Litchford*

Deep space transportation capability for science and exploration is fundamentally limited by available propulsion technologies. Traditional chemical systems are performance plateaued and require enormous Initial Mass in Low Earth Orbit (IMLEO) whereas solar electric propulsion systems are power limited and unable to execute rapid transits. Nuclear based propulsion and alternative energetic methods, on the other hand, represent potential avenues, perhaps the only viable avenues, to high specific power space transport evincing reduced trip time, reduced IMLEO, and expanded deep space reach. Here, key deep space transport mission capability objectives are reviewed in relation to STMD technology portfolio needs, and the advanced propulsion technology solution landscape is examined including open questions, technical challenges, and developmental prospects. Options for potential future investment across the full complement of STMD programs are presented based on an informed awareness of complimentary activities in industry, academia, OGAs, and NASA mission directorates. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL

Session 13

National Chairpersons:

Neil Dennehy, NASA Goddard Space Flight Center

Stephen “Phil” Airey, ESA TEC-ECC

Local Chairpersons:

Kristen Francis, Lockheed Martin Space Systems Company

James Cook, Sierra Nevada Corporation

The following paper was not available for publication:

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The following paper numbers were not assigned:

AAS 16-139 to -140

MOVING GEOLOCATION HOME FROM SPACE

Joseph Boardman,[*] Daniel Cervantes[†] and William Frazier[‡]

Traditional space remote sensing systems invest large amounts of resources into ensuring that the space-based GN&C hardware and software supports essentially open-loop geolocation of imagery, based on precision attitude and ephemeris data, and numerous biases and correction factors, many of which must be constantly re-evaluated (e.g. alignments). Ground-based geolocation is typically assumed to be too risky, slow, and/or expensive to be considered anything but "Plan B", or an ancillary upgrade. However, with the ever-growing processing capabilities, current available ground software packages have made it possible to perform image orthorectification using only the image data (seeded with relatively course GN&C information), leveraging various feature recognition algorithms as an operationally-viable solution. Such algorithms have been developed of necessity for certain particular mission classes (e.g. small bodies and hosted payloads), and also have become commercially available for Earth applications. In this paper we evaluate the performance available from representative algorithms, and consider the implied system architecture trades of potentially foregoing the traditional high-performance GN&C solution altogether, in favor of currently-available ground processing. This can then become a mission-enabling strategy for low-cost Earth remote sensing missions such as NASA's Earth Ventures class. [View Full Paper]

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AAS 16-132

OBSERVABILITY AND SOLUTION TECHNIQUES FOR RANGE-ONLY RELATIVE NAVIGATION

John A. Christian*

There are a number of emerging and important operational scenarios where range-only relative navigation may be desirable — such as a formation of CubeSats capable of performing inter-satellite ranging over a UHF/VHF communications link. Despite the existence of such scenarios, little published work exists on the problem of range-only relative navigation. The present work explores the observability of range-only relative navigation and establishes that there are four possible relative trajectories for general 3D motion that will produce exactly the same time history of range measurements. Various special relative orbits can produce other multiplicities of possible relative trajectories, such as two, eight, or infinitely many. After establishing that multiple solutions exist (two, four, eight, or infinitely many), a straightforward method for quickly computing these solutions is described. The results are demonstrated through a number of numerical examples.

[View Full Paper]

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AAS 16-134

AN ADVANCED ARCHITECTURE FOR OPTIMIZING EARTH SCIENCE DATA COLLECTION BASED UPON MODEL PREDICTIVE CONTROL

Michael Lieber,[*] Carl Weimer,[†] Reuben Rohrschneider[‡] and Lyle Ruppert[§]

The increasing importance of maneuverable and distributed space-based sensor systems has led to exciting developments in large-scale data extraction software and synthesis of complex and enhanced data products. However, beyond spacecraft attitude control system retargeting, the ability to optimize data collection real-time at the sensor level is very limited and constrains the use of plat-forms with coordinated control and instruments with multiple degrees of freedom. Further work is needed on the lower level, autonomous software to enable fast, optimized control. Two examples of such systems are adaptive lidar and tight formation flying control of future U Class missions. Under NASA Earth Science Technology Office funding, Ball is developing a local, multi-layered control system architecture which communicates with a higher level software layer. The local control formulation is based upon an architecture known as Model Predictive Control (MPC). MPC has found use in many different complex systems where the controlled system is characterized as multivariable, with multiple constraints and possibly nonlinear interactions. These include robotic vision systems, chemical processing, and quad-rotor craft and have been proposed for formation flying spacecraft. MPC optimizes the data collection at each time step from higher level constraints and commands and is enabled by the increased computational power available in field programmable gate arrays (FPGA) implementations. We discuss development of the MPC architecture for a type of adaptive lidar called Electronically Steerable Flash Lidar (ESFL).[1] ESFL has potentially hundreds of individually steerable laser beamlets and when combined with other sensors pose a large real-time optimization problem well suited to the MPC architecture. The paper then discusses ways to incorporate an estimator for lidar power return with an evolving scene. [View Full Paper]

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ASTRIX 1090 FIBER OPTIC GYRO SUCCESS PAVES THE WAY FOR THE FUTURE DEVELOPMENT

Anaïs Ardan,* Steve Masson,* Gilbert Cros,† Sébastien Ferrand,‡ Steeve Kowaltschek,§ Phil Airey,§ Jeroen Vandersteen§ and Guillaume Delavoipiere**

In the early 2000s, AIRBUS DS SAS developed, in collaboration with a French SME, Ixspace, and with CNES and ESA support, a family of inertial reference units (IRU) for a large range of space applications. This family of products, called "Astrix™", is based on solid-state Fibre Optic Gyro (FOG) technology with the Astrix 200 and Astrix 120 providing high performance solutions. The latest development in the family, the Astrix 1000 series, was dedicated to mid-to-higher level performance satellite applications.

As for all previous Astrix products, the 1000 series benefits from all the advantages of the FOG technology for space applications, in particular: low noise, high resolution, high reliability, no life limited items and low power consumption. While the first Astrix generation design was performance driven, the objective of the newer Astrix 1000 "plug & play" series is to provide more cost effective and compact solutions for satellites, cruise vehicles and lander modules while still providing medium to high inertial performances. During the AAS GN&C 2014 conference, a paper on the 1000 series presented the innovative solutions implemented in this new development. Since then, the first version of the series, Astrix 1090, was successfully qualified and met a very good commercial success in both the commercial telecom market and for scientific applications.

In the meantime some new developments have also been initiated in the frame of ESA and CNES contracts to enlarge the Astrix 1000 series. Two main goals are: i) to ensure the market availability of a more compact and capable high performance IMU (including accelerometers), and ii) to propose a more affordable and compact medium performance IRU solution for future telecom platforms such as Neosat. Because of its strong heritage with the recently qualified product, this new version was named Astrix 1090 NEO.

After an introduction on the background of the Astrix family, and the qualification of the Astrix 1090, this paper will present the new development of NEO version to enable a "plug & play" IMU providing reduced mass and power and at the same time lower cost.

[View Full Paper]

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AAS 16-136

IRES-C: A NEW, MODULAR, MEDIUM ACCURACY EARTH HORIZON SENSOR FOR EARTH POINTED SAFE MODE ON LEO SATELLITES

F. Boldrini,[*] S. Brogi,[*] P. Fidanzati,[*] M. Morresi[*] and D. Procopio[*]

Finmeccanica started to develop Infrared Earth Sensors (IRES) for the Earth horizon detection in the mid-1960s. Since then, several “generations” of IRES have followed. Today, the IRES N2 product represents the pinnacle of Finmeccanica’s high-accuracy Earth Horizon detection sensors and is used both in TLC satellites in GEO orbit, as well as in the GALILEO GNSS Constellation in MEO orbit.

Market demand for Earth Sensors for Earth Pointed Safe Mode on LEO Satellites has led Finmeccanica to develop IRES-C, a new, medium accuracy Earth Horizon sensor, suitable to be used as a backup or safe mode unit. The IRES-C sensor (the C stands for Coarse) was engineered to operate at a nominal altitude of 625 Km but able to cover a range from 400km to 850km with slightly degraded performance. The IRES-C sensor for LEO applications was designed for ease-of-use (it includes features such as a digital interface giving digitalized signals proportional to the Earth position in the sensor FOV, Smart Pitch and Roll reconstruction algorithms and calibration implemented at the AOCS level and simplified stimuli for end-to-end workmanship verification, etc.) and to be price competitive.

IRES-C is a cost effective alternative (with lower performance) to the IRES N2 for GEO and MEO orbits able to operate in LEO orbits, where the IRES N2 cannot. The IRES-C Earth sensor was developed in the frame of two ESA Contracts during which the IRES-C architecture was defined and verified by testing on an Engineering Model (EM) configured for GEO applications.

A preliminary LEO configuration of the IRES-C product was also studied in the frame of the same contracts. The results of these studies and the final LEO configuration of the IRES-C are described in the paper. [View Full Paper]

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STRAIN ACTUATED SOLAR-ARRAYS FOR PRECISION POINTING OF SPACECRAFT

Oscar Alvarez-Salazar,[*] Jack Aldrich,[†] Nuno Filipe,[‡] James Allison[§] and Soon-Jo Chung[**]

Next generation telescopes for space exploration are being planned with unprecedented levels of pointing and wavefront stability as science enabling capabilities - i.e., sub-milli-arcsecond class pointing, and pico-meter class RMS wave-front error). Current methodologies for attaining these levels of stability are approaching the limit of what is possible with the use of isolation, intensive and risky structural dynamic tailoring, exquisite broad-band Attitude Control System (ACS) sensors and actuators, and ultra-precise fast steering mirrors commanded to compensate for pointing errors through feedback of camera measurements. This paper explores the benefits of using Strain Actuated Solar Arrays (SASA) - currently under Research at the Jet Propulsion Laboratory and the University of Illinois Urbana Champagne - in new ACS architectures for applications requiring very tight precision pointing of a SC and on-board instrumentation. A strain actuated solar array has the following characteristics: (1) Strain actuation and sensing is distributed throughout the SA panels to obtain control authority and observability over the strain state of the SA–enabling SA jitter control. (2) Large motion (up to 10 degrees or relative motion) strain based mechanisms are used in between SA panels and in between the SC and the solar array–enables SC slewing and limited momentum management. (3) The mechanical (i.e., stiffness and configuration) and inertia/mass properties of the SA have been designed to optimize its ability to control its vibrations and the vibration and attitude of the host SC. This paper discusses ACS architectures that use the above SASA system while avoiding the use of the Reaction Wheel Actuator (RWA) during key science observation periods. The RWA being the dominant source of pointing jitter and wave front jitter in a telescope based observatory; hence, not flying RWAs amounts to not flying the main source of jitter! At least two architectures based on the SASA system are studied - one is an earth orbiter, the other is assumed to be in an L2 orbit. Simulation results for one of these cases are discussed along with what developments are needed going forward to enable the use of this technology. [View Full Paper]

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AAS 16-138

MODELLING OF SPACECRAFT WITH *N* REACTION WHEELS USING ARBITRARY ATTITUDE PARAMETERIZATIONS

Alex Walsh,[*] David Evan Zlotnik[*] and James Richard Forbes[†]

Spacecraft pointing, slewing, and trajectory tracking hinge on precise attitude estimation and control. Analysis, design, and commissioning of attitude and estimation algorithms relies on an accurate kinematic and dynamic model. In this paper, modelling of a spacecraft with *N* reaction wheels is presented using a Lagrangian formulation. The derivation is accomplished in matrix form using an arbitrary attitude parameterization. Simulation results are presented validating the derivation. A discussion of reaction wheel speed versus torque control is also included. [View Full Paper]

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RECENT EXPERIENCES IN GUIDANCE, NAVIGATION AND CONTROL

Session 14

National Chairpersons:

Bill Frazier, Jet Propulsion Laboratory / California Institute of Technology

Scott Glubke, NASA Goddard Space Flight Center

Local Chairpersons:

Michael Osborne, Lockheed Martin Space Systems Company

Scott Mitchell, Ball Aerospace & Technologies Corp.

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AAS 16-148 to -150

AAS 16-141

NEW HORIZONS GUIDANCE & CONTROL & PROPULSION SYSTEMS BUDGET VERSUS PERFORMANCE FOR THE PLUTO ENCOUNTER

Gabe D. Rogers,[*] Sarah H. Flanigan,[†] Stewart Bushman,[‡] Chris Hersman,[§] Valerie Mallder,[**] Madeline Kirk,[††] Hollis Ambrose[‡‡] and Leslie Young[§§]

The New Horizons spacecraft flew by Pluto on July 14, 2015, completing the first close up encounter of the Pluto system. The nine-day core command sequence surrounding closest approach was packed with 371 pointed maneuvers supporting observations and consumed approximately 6 kg of propellant. Inflight attitude data has been used to assess the performance of the guidance & control and propulsion systems and compare the results to pre-encounter estimates and simulations. In addition to the 9 days around closest approach, the spacecraft conducted science-pointing activities formally beginning on January 15, 2015 and concluded on July 30, 2015. To assure that the spacecraft had adequate resources to support all of the science requirements, a detailed budget of thruster cycles (open/close of each thruster) and propellant used was developed years in advance. Each maneuver and event was modeled and eventually simulated using assumptions and historic performance. This paper will present the various phases in the budgeting process, how the models and high fidelity simulations were validated, and how the real encounter numbers compared with the budgets. This paper will also document two different methods employed for tracking propellant usage, and how the type of maneuvers and events influenced the relationship between the two methods. [View Full Paper]

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AAS 16-142

CASSINI NAVIGATION: THE ROAD TO CONSISTENT SUB-KILOMETER ACCURACY SATELLITE ENCOUNTERS[*]

Julie Bellerose,[†] Sumita Nandi,[‡] Duane Roth,[§] Zahi Tarzi,[**] Dylan Boone,[**] Kevin Criddle[**] and Rodica Ionasescu[**]

This paper reviews the orbit determination performance for the last five years of the Cassini Mission Solstice Tour. During this period of time, Cassini had more than 30 satellite encounters, including Titan, Rhea, and Dione. We report on the navigational flyby accuracy, comparing post-flyby reconstructions and encounter predictions, and discuss the performance improvement and challenges over the years. Finally, we give an overview of the "Grand Finale" end of mission planned for 2017. [View Full Paper]

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AAS 16-143

ORION EXPLORATION FLIGHT TEST-1 POST-FLIGHT NAVIGATION PERFORMANCE ASSESSMENT RELATIVE TO THE BEST ESTIMATED TRAJECTORY

Robert S. Gay,* Greg N. Holt† and Renato Zanetti‡

This paper details the post-flight navigation performance assessment of the Orion Exploration Flight Test-1 (EFT-1). Results of each flight phase are presented: Ground Align, Ascent, Orbit, and Entry Descent and Landing. This study examines the on-board Kalman Filter uncertainty along with state deviations relative to the Best Estimated Trajectory (BET). Overall the results show that the Orion Navigation System performed as well or better than expected. Specifically, the Global Positioning System (GPS) measurement availability was significantly better than anticipated at high altitudes. In addition, attitude estimation via processing GPS measurements along with Inertial Measurement Unit (IMU) data performed very well and maintained good attitude throughout the mission.

[View Full Paper]

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AAS 16-144

LAUNCH AND COMMISSIONING THE DEEP SPACE CLIMATE OBSERVATORY

Nicholas P. Frey[*] and Edward P. Davis[†]

The Deep Space Climate Observatory (DSCOVR), formerly known as Triana, successfully launched on February 11th, 2015. To date, each of the five spacecraft attitude control system (ACS) modes have been operating as expected and meeting all guidance, navigation, and control (GN&C) requirements, although since launch, several anomalies were encountered. While unplanned, these anomalies have proven to be invaluable in developing a deeper understanding of the ACS, and drove the design of three alterations to the ACS task of the flight software (FSW). An overview of the GN&C subsystem hardware, including refurbishment, and ACS architecture are introduced, followed by a chronological discussion of key events, flight performance, as well as anomalies encountered by the GN&C team. [View Full Paper]

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AAS 16-145

CELESTIAL ASPECTS OF MARS SCIENCE LABORATORY CHEMCAM SUN-SAFETY

Stephen Peters,[*] Lauren DeFlores,[†] Noah Warner[‡] and Todd Litwin[§]

The Mars Science Laboratory ChemCam instrument is sensitive to the sun, has no sun cover, yet points in the same direction as other instruments that regularly image the sun for science observations and attitude determination. It is also repointed as a side effect of mobility. Within a "sun-safe" focal range, the ChemCam can tolerate the sun passively passing through its field of view at Mars rotation rate. It can also tolerate up to three minutes of repointing with the sun remaining within its field of view. In the "sun-unsafe" focal range used for ChemCam observations, the sun must never be allowed to enter the ChemCam field of view. Since this applies even in the event of a system fault, ChemCam observations are only allowed in directions guaranteed to be "sun-free" for several sols of Mars rotation and orbital motion. The ChemCam is protected by flight software enforcement of sun safety constraints and by models of these constraints implemented within ground tools used in tactical operations. In addition, a special sun search strategy, guaranteeing ChemCam sun safety despite the lack of knowledge of the geometric relationship between the ChemCam boresight and the vector to the sun, had to be developed for initial attitude determination. [View Full Paper]

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AAS 16-147

THE LIRIS-2 3D IMAGING LIDAR ON ATV-5

Florian M. Kolb, Michael Windmüller, Mario Rößler, Bettina Möbius,[*] Pierre Casiez, Bruno Cavrois[†] and Olivier Mongrard[‡]

The flight of the European supply vessel ATV-5 “Georges Lemaître” to the International Space Station included a demonstrator for a new set of optical sensors for non-cooperative rendezvous and docking, called “LIRIS” (Laser Infra-Red Imaging Sensors). As part of this project, a prototype for a new 3D Imaging LIDAR was developed, integrated and tested by Jena-Optronik for Airbus Defence and Space and ESA. This LIRIS LIDAR was based on technology from the DLR project “LiQuaRD” (LIDAR Qualification for Rendezvous and Docking) and allowed for the recording of high-resolution 3D images during the approach of ATV to the ISS. We will describe the design approach, properties and advantages of the LIRIS-2 sensor as well as the types of data returned by the sensor. [View Full Paper]

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POSTER SESSION

Session 15

Local Chairperson:

Cheryl Walker, Lockheed Martin Space Systems Company

The following papers were not available for publication:

AAS 16-152 "Methods for a Non-Iterative Solution to Angles-Only Inertial Relative Orbit Determination," A. Ceniceros, University of Arizona (Poster Only)

AAS 16-153 "Simulating the Wheel World: Reaction Wheel Simulators for Small Satellite Avionics Testing," W. Jantscher, United States Air Force Academy (Poster Only)

AAS 16-154 "Compact Magnetic Torque Bars," J. Krebs, Cayuga Astronautics (Poster Only)

AAS 16-155 "Adaptive Control System for CubeSat Attitude," A. Probe, Texas A&M University (Poster Only)

AAS 16-157 "Freewheelin: Reaction Wheel Motor Sizing and Torque Analysis for EyasSAT3," T. Townley, United States Air Force (Poster Only)

AAS 16-158 "Validation of Inverse Mapping Algorithms for Analytically Propagating Nonlinear Probability Density," A. B. Younes, Khalifa University, Abu Dhabi, UAE (Poster Only)

AAS 16-159 "Assessment of uSat Constellation for a Small Body Science Mission," W. Frazier and K. Reh, NASA (Poster Only)

The following paper number was not assigned:

AAS 16-160

AAS 16-151

OBSERVATIONS ON THE GEOMETRY OF HORIZON-BASED OPTICAL NAVIGATION

John Christian*, and Shane Robinson†

NASA's Orion Project has sparked a renewed interest in horizon-based optical navigation (OPNAV) techniques for spacecraft in the Earth-Moon system. Some approaches have begun to explore the geometry of horizon-based OPNAV and exploit the fact that it is a conic section problem. Therefore, the present paper focuses more deeply on understanding and leveraging the various geometric interpretations of horizon-based OPNAV. These results provide valuable insight into the fundamental workings of OPNAV solution methods, their convergence properties, and associated estimate covariance. Most importantly, the geometry and transformations uncovered in this paper lead to a simple and non-iterative solution to the generic horizon-based OPNAV problem. This represents a significant theoretical advancement over existing methods. Thus, we find that a clear understanding of geometric relationships is central to the prudent design, use, and operation of horizon-based OPNAV techniques. [View Full Paper]

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AAS 16-156

GENERAL HINGED SOLAR PANEL DYNAMICS APPROXIMATING FIRST-ORDER SPACECRAFT FLEXING

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For many spacecraft with deployable structural components, such as solar panels or deployable antennas, the rigid-body assumption does not accurately model the full system dynamics. Spacecraft with large deployed solar panels exhibit flexible dynamics that can impact the final pointing and jitter performance of an attitude control system, or the simulation of an on-board accelerometer. For simulation and analysis purposes, it is desirable to include approximate flexible dynamics in a manner that easily integrates with the rigid body translational and rotational equations of motion. Current methods either require extensive derivation to implement flexible dynamics into the simulation or do not provide enough fidelity. This paper introduces a first-order model of the flexible dynamics using hinged multi-body dynamics that is applicable to a range of spacecraft shapes and configurations, but fully accounts for three-dimensional motion of this component. The formulation assumes the appended bodies are rigid bodies, and are connected to a main rigid body (hub) by a single degree of freedom torsional hinge. The numerical simulations are validated through a range of energy and momentum checks. A simple example of a simulation is included and highlights the necessity to include flexing for certain spacecraft.

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