GUIDANCE AND CONTROL 2013

Edited by
Lisa R. Hardaway

American Astronautical Society

Volume 149
ADVANCES IN THE ASTRONAUTICAL SCIENCES

GUIDANCE AND CONTROL 2013

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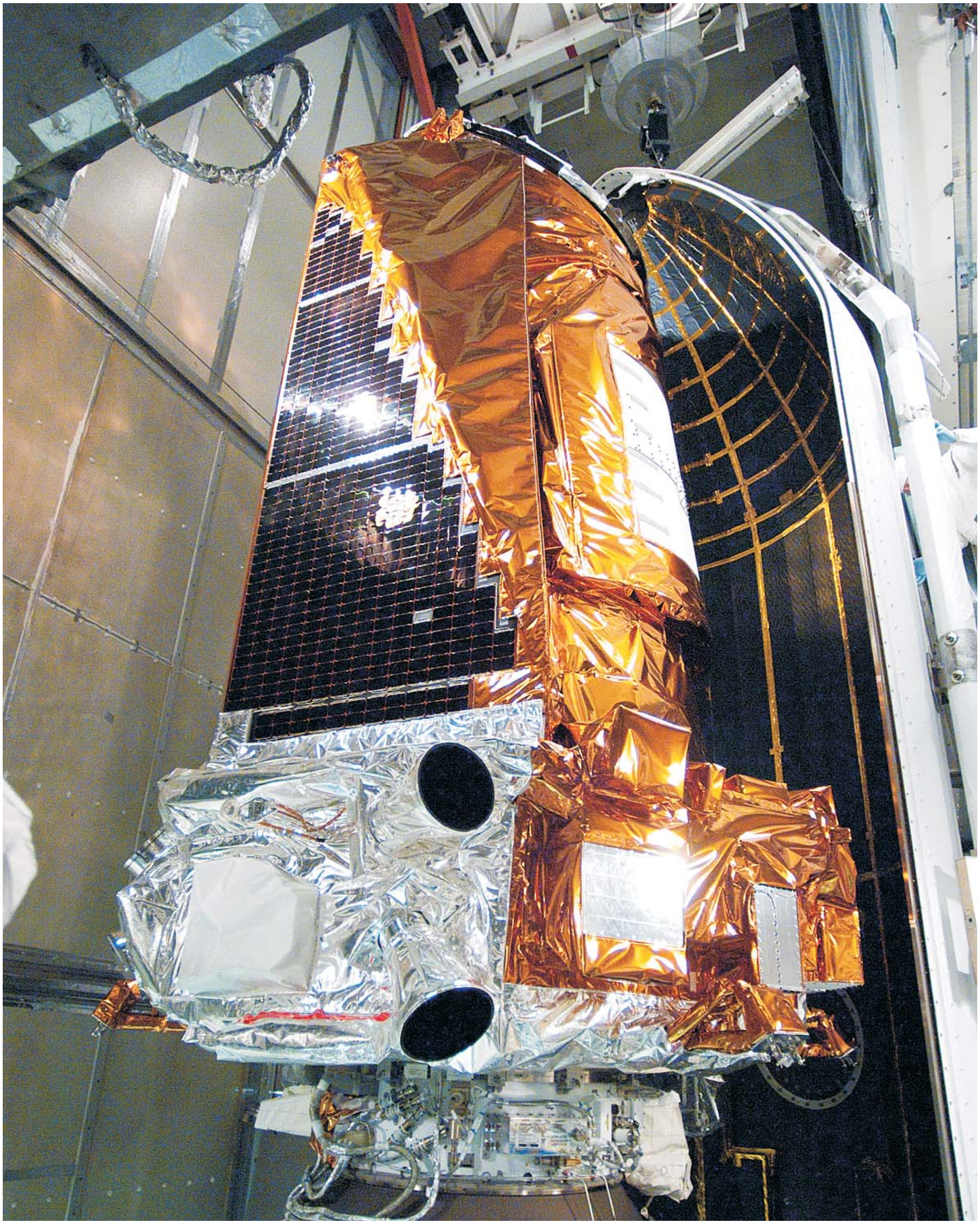
Front Cover Illustration:

The beautiful imagery and important science received from on-orbit telescopes would not be possible without the technologies of Guidance, Navigation and Control. (Photo Credit: NASA).

Frontispiece:

Kepler, with its star trackers visible, is installed into its launch fairing. (Image courtesy of Ball Aerospace & Technologies Corp.)



GUIDANCE AND CONTROL 2013

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FOREWORD

HISTORICAL SUMMARY

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

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

Back in Denver, Bud and Don approached the AAS Section Chair, Bob Culp, with their proposal. In 1977, Bud Gates, Don Parsons, and Bob Culp organized the first conference, and began the annual series of meetings the following winter. Dan and Lou were delighted to see their concept brought to reality and joined enthusiastically from afar. In March 1978, the First Annual Rocky Mountain Guidance and Control Conference met at Keystone, Colorado. It met there for eighteen years, moving to Breckenridge in 1996 where it has been for the last 18 years. The 2013 Conference was the 36th Annual AAS Rocky Mountain Guidance and Control Conference.

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

The style was established at the first Conference, and has been adhered to strictly until 2013. No parallel sessions, three-hour technical/tutorial sessions at daybreak and late afternoon, and a six-hour ski break at midday are the biblical constraints. 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 that more than justified the hard play between sessions.

After the 2012 conference, it was clear that overall industry budget cuts and a mis-conception by industry and government leaders that this conference was a ski trip with a few side conversations were leading to reduced attendance and support. In an effort to meet the needs of the constituents, several changes were suggested that did not meet the original founding style. The first implementation of these changes was to add parallel sessions for 3 of the 8 sessions on a trial basis during the 2013 conference and was welcomed by most attendees.

A tradition from the beginning and retained in 2013 has been the Conference banquet. It is an elegant feast marked by informality and good cheer. A general interest speaker has been a popular feature. The banquet speakers have been:

Banquet Speakers

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

2006 Mary E. Kicza, Deputy Assistant Administrator for Satellite and Information Services, NASA, "NOAA: Observing the Earth from Top to Bottom."

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

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

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

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

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

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

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

OBSERVATIONS: CHALLENGES AND RESPONSIBILITIES

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

Tutorials

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

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

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

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

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

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

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

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

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

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

1988	Professor Arthur E. Bryson, Stanford University, "Software Application Tools for Modern Controller Development and Analysis."
1989	Professor John L. Junkins, Texas A&M University, "Practical Applications of Modern State Space Analysis in Spacecraft Dynamics, Estimation and Control."
1990	Professor Laurence Young, Massachusetts Institute of Technology, Aerospace Human Factors."
1991	The Low-Earth Orbit Space Environment Professor G. W. Rosborough, University of Colorado, "Gravity Models." Professor Ray G. Roble, University of Colorado, "Atmospheric Drag." Professor Robert D. Culp, University of Colorado, "Orbital Debris." Dr. James C. Ritter, Naval Research Laboratory, "Radiation." Dr. Gary Heckman, NOAA, "Magnetics." Dr. William H. Kinard, NASA Langley, "Atomic Oxygen."

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

From the beginning the Conference has provided extensive support for students interested in aerospace guidance and control. The Section, using proceeds from this Conference, annually gives $2,000 in the form of scholarships at the University of Colorado, one to the top Aerospace Engineering Sciences senior, and one to an outstanding Electrical and Computer Engineering senior, who has an interest in aerospace guidance and control. The Section has assured the continuation of these scholarships in perpetuity through a $70,000 endowment. The Section supports other space education through grants to K-12 classes throughout the Section at a rate of over $10,000 per year. All this is made possible by this Conference.

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

Scholarship Winners

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

In 2013, in an effort to obtain more 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 address hardware and software research as well as component, system, or simulation advances. Papers submitted must have a student as the primary author and presenter. 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. The SpaceX Grand Prize Award for Excellence in the field of GN&C by a Student was awarded.

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."

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

	Conference Chair	Attendance
1978	Robert L. Gates	83
1979	Robert D. Culp	109
1980	Louis L. Morine	130
1981	Carl Henrikson	150
1982	W. Edwin Dorroh, Jr.	180
1983	Zubin Emsley	192
1984	Parker S. Stafford	203
1985	Charles A. Cullian	200
1986	John C. Durrett	186
1987	Terry Kelly	201
1988	Paul Shattuck	244
1989	Robert A. Lewis	201
1990	Arlo Gravseth	254
1991	James McQuerry	256
1992	Dick Zietz	258
1993	George Bickley	220
1994	Ron Rausch	182
1995	Jim Medbery	169
1996	Marv Odefey	186
1997	Stuart Wiens	192
1998	David Igli	189
1999	Doug Wiemer	188
2000	Eileen Dukes	199
2001	Charlie Schira	189
2002	Steve Jolly	151
2003	Ian Gravseth	178
2004	Jim Chapel	137

2005	Bill Frazier	140
2006	Steve Jolly	182
2007	Heidi Hallowell	206
2008	Michael Drews	189
2009	Ed Friedman	160
2010	Shawn McQuerry	189
2011	Kyle Miller	161
2012	Michael Osborne	140
2013	Lisa Hardaway	181

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

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

On behalf of the Conference Committee and the Section,

Lisa R. Hardaway, Ph.D.
Ball Aerospace & Technology Corp.
Boulder, Colorado

PREFACE

This year marked the 36th anniversary of the AAS Rocky Mountain Section's Guidance and Control Conference. It was held in Breckenridge, Colorado at the Beaver Run Resort on February 1-6, 2013. This year was also the first year of an expected several years of reformatting to be more in-line with industry expectations and government budgets. The planning committee and the national chairs took this in stride and created an excellent conference experience. I thank all deeply for their hard work and flexibility. Despite the looming threat of Sequestration and several cancellations by government employees, the attendance kept steady at 181, most likely due the parallel sessions and increased student attendance.

The conference formally began on the morning of February 2nd with a new session of student papers chaired by Dr. Tim Crain, the Morpheus Flight Dynamics Lead at NASA's Johnson Space Center. This session was designed to embrace the wealth of research and innovative projects related to spacecraft GN&C being accomplished in the university setting. Papers submitted had a student as the primary author and presenter and were 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. The SpaceX Grand Prize Award for "Excellence in the Field of GN&C by a Student" was awarded.

Due to scheduling conflicts, our keynote speaker took the stage in the late afternoon instead of the traditional morning slot. Mr. Gentry Lee of the Jet Propulsion Laboratory spoke to "From Viking to Curiosity: Reflections on the Exploration of Mars." Closely following the successful landing of *Curiosity*, the GN&C community appreciated the inside looks at entry, descent and landing capabilities through the years.

To cap off the day, the *Technical Exhibits* session was held in the afternoon. Twenty-four companies participated in the technical exhibits with many hardware demonstrations as well as fostering excellent technical interchanges between conferees, vendors, and family. Students from Monarch High School in Louisville, Colorado and from several universities also participated. The session was accompanied by an excellent buffet dinner. Many family members and children were present, greatly enhancing the collegiality of the session. The highly experienced team of Kristen Scott and Meredith Larson did an outstanding job organizing the vendors and exhibits.

February 3rd began with the first ever parallel sessions, *Advances in GN&C Software* and *Advances in GN&C Hardware*. The response to the request for papers for both sessions was enormous and both sessions were well attended. After an educational workshop presented by Math Works, Inc. entitled "Model-based Design of Satellite Dynamics" for those interested in the development and implementation of a satellite spin-stabilized control method, the afternoon session continued in the parallel vein with *Human Spaceflight GN&C*,

addressing the new paradigms of GN&C concepts applied to human spaceflight and *Position Navigation and Timing*, which concentrated on global positioning systems.

Monday morning the 4th of February was devoted to a long but exciting session *Entry, Descent and Landing Flight Dynamics*. Topics ranged from Mars landers to closed-looped test beds. Prior to the banquet in the evening, a foreshortened but fun afternoon session addressed possible future developments in *GN&C Beyond 2022*.

Thomas J. "Dr. Colorado" Noel, Ph.D., Professor of History and Director of Public History, Preservation & Colorado Studies at University of Colorado Denver entertained the attendees with a presentation entitled "Welcome to the Highest State: A Quick History of Colorado." The banquet food was excellent, as usual, thanks to the great staff at Beaver Run and the conference's own Kristen Scott.

Tuesday, February 5th continued with a warm trend outside while inside attendees were treated to several excellent papers about *GN&C Operations Around Asteroids and Comets*. Four missions were discussed as well as some advanced technologies. The afternoon brought another set of parallel sessions, *Rendezvous, Proximity Operations and Docking* and *Nested Control Loops Leveraging Payload Capabilities*. Both sessions provided insight into these important GN&C topics.

The conference wrapped up on the morning of the 6th with the ever popular *Recent Experiences* session. The valuable lessons purveyed in this session by our most experienced colleagues will go a long ways toward creating successful missions in the future.

Overall, the 36th annual conference was interesting and engaging, with many unique experiences. Technically, we are maintaining the high standards set by our predecessors while welcoming a new generation of conferees to continue the traditions of our founders. The technical committee, session chairs, and national chairs were a pleasure to work with. Special thanks go to both Carolyn O'Brien of Lockheed Martin and Liz Garret from Ball Aerospace for their abilities to herd the engineers, physicists, and mathematicians in the right direction, as well as keep me on-track and sane throughout the process.

Lisa Hardaway, Ph.D., Conference Chairperson
2013 AAS Guidance and Control Conference

CONTENTS

STUDENT PAPER SESSION

SESSION I

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 address hardware and software research as well as component, system, or simulation advances. Papers submitted must have a student as the primary author and presenter. Papers will be 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. The session is limited to 7 papers with the top 3 papers receiving awards.

National Chairperson: Tim Crain, NASA Johnson Space Center

Local Chairpersons: Dave Chart, Lockheed Martin Space Systems

Ian Gravseth, Ball Aerospace & Technologies Corp.

The following paper was not available for publication:

AAS 13-013
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 13-018 to -020

LABORATORY EXPERIMENTS SUPPORTING AUTONOMOUS SPACE DEBRIS MITIGATION

Kurt A. Cavalieri,[*] Brent Macomber,[*] Clark Moody,[*] Austin Probe[*] and John L. Junkins[†]

High fidelity ground-based simulation is a necessary step in the development of successful autonomous orbital debris removal missions. A guidance, navigation, and control package is presented, which supports such experiments. A structured light stereo sensor delivers three-dimensional point cloud data to an object recognition module. The resulting navigation solution comprises the relative position and attitude of a tumbling target vehicle with respect to the capture vehicle. An onboard filter consumes these relative vision measurements along with data from an inertial measurement unit, providing a mission handler with the best estimate of relative position and attitude. Built on an event-driven framework, the controller maximizes target visibility to the vision sensor and drives a probe down the throat of the target nozzle. A dynamic vehicle emulator translates the motion of a virtual spacecraft of choice into real motion of the robotic experimental platform. This paper presents the object recognition algorithm, filter and control components, and calibration procedures used in the development of the GNC package along with experimental results for two mission scenarios. [View Full Paper]

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AAS 13-012

ELECTROMAGNETIC FORMATION FLIGHT CONTROL USING DYNAMIC PROGRAMMING

Gregory J. Eslinger[*] and Alvar Saenz-Otero[†]

Electromagnetic formation flight (EMFF) is an enabling technology for a number of spacecraft mission architectures. The RINGS program will be the first time EMFF is demonstrated in a microgravity environment. Nonlinearities due to magnetic field interactions preclude linear feedback controllers from being used to control the RINGS system. Approximate dynamic programming is explored in this paper as a potential method for developing a controller. Aggregation and cost approximation methods are used to develop the cost-to-go of the system. Direct input and rollout architectures are presented for building a controller based on the cost-to-go. Aggregation and cost approximation methods are both able to produce a valid cost-to-go for the RINGS system. Both direct input and rollout control architectures are able to drive the system to the desired state given a cost-to-go, with the rollout architecture performing on the same level as a direct input controller. Overall, dynamic programming was successful in developing a working RINGS controller. [View Full Paper]

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USING SIGNALS OF OPPORTUNITY FOR DEEP SPACE SATELLITE NAVIGATION

Ryan Handzo,* Kenn Gold,† George Born‡ and Michael Davies§

Satellite navigation traditionally uses GPS signals, or when GPS is unavailable, dedicated ground based signals. The use of GPS is limited to specific orbital regimes and has very limited availability beyond geosynchronous altitudes, while dedicated ground-based signals are expensive and specific to each mission. The use of generic terrestrially broadcast signals, or Signals of Opportunity, for use in satellite navigation has not yet been studied in great depth. This paper presents analysis that shows that these Signals of Opportunity are useful signals that can be picked up in GPS challenged environments as well as for deep-space orbital tracking. Furthermore, it is shown that not only are the signals available in these GPS challenged regimes, but they include many properties that allow satellite navigation in these GPS challenged regimes; including number of signals seen, uniqueness of each signal, and ability to range each signal to determine source of signal and ephemeris of receiver. These Signals of Opportunity present a new and economical method for satellite positioning, navigation, and timing in a wide variety of orbits out to lunar distance and beyond. [View Full Paper]

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DAYSTAR: MODELING AND TESTING A DAYTIME STAR TRACKER FOR HIGH ALTITUDE BALLOON OBSERVATORIES

Nicholas Truesdale,[*] Kevin Dinkel,[*] Zach Dischner[*] and Jed Diller[†]

High altitude balloon platforms offer improved accessibility for astronomical observatories with performance comparable to the Hubble Space Telescope. A requisite for such missions is an attitude determination system that provides an error signal with sub-arcsecond accuracy. Star trackers are a common solution, but none currently perform with the required accuracy due to atmospheric scattering during daytime. DayStar, a prototype star tracker designed at the University of Colorado at Boulder, addresses this issue with the use of red-filtered optics, a custom high resolution CMOS camera and efficient star identification algorithms. This paper discusses the modeling required to quantify daytime performance, and compares it to experimental data from DayStar's September, 2012 test flight. Both show that, despite daytime conditions in the stratosphere, a star tracker can operate with sub-arcsecond accuracy. With the capabilities that DayStar provides, a high altitude balloon observatory can match the image quality of Hubble for a fraction of the cost. [View Full Paper]

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AAS 13-016

ANGULAR RATE ESTIMATION FROM GEOMAGNETIC FIELD MEASUREMENTS AND OBSERVABILITY SINGULARITY AVOIDANCE DURING DETUMBLING AND SUN ACQUISITION

Christopher M. Pong* and David W. Miller†

Knowledge of a spacecraft's angular rate is essential for many spacecraft control laws during various mission phases. In this paper, an extended Kalman filter (EKF) is developed to estimate the angular rate of a spacecraft in low-Earth orbit using geomagnetic field measurements from a magnetometer. This EKF can therefore provide rate estimates on a spacecraft without gyros or where the gyros have failed. Flight telemetry from the RXTE mission has been used along with "truth" gyro measurements to validate this EKF. A nonlinear, local observability test has been applied to this problem and it is shown that there are conditions where observability in the direction of the magnetic field is lost. Approaching these singularities can result in divergence of the EKF. Two novel singularity avoidance techniques are developed for two common mission modes: detumbling and Sun acquisition. It is shown in simulation that these control algorithms are able to avoid these observability singularities, maintain low estimation covariance, and successfully achieve the mode objectives. [View Full Paper]

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AAS 13-017

HIGH ORDER OPTIMAL TRACKING CONTROL SENSITIVITY CALCULATIONS USING COMPUTATIONAL DIFFERENTIATION

Ahmad Bani Younes,[*] James D. Turner[†] and John L. Junkins[‡]

An optimal tracking control is developed where the optimal control is calculated by optimizing a universal quadratic penalty. The optimal tracking problem formulation is generalized by modeling the control gains as a Taylor series in the parameter uncertainty. The generalized control formulation is computed as an off-line calculation for the sensitivity gains. The goal of the generalized control formulation is to eliminate the need for gain scheduling for handling model parameter variations. An estimator is assumed to be available for predicting the model parameter changes. Higher-Order control sensitivity calculations are applied on the full nonlinear model using computational differentiation tool. Several attitude error representations are presented for describing the tracking orientation error kinematics. Compact forms of attitude error equation are derived for each case. The attitude error is initially defined as the quaternion (rotation) error between the current and the reference orientation. Transformation equations are presented that enable the development of nonlinear kinematic models that are valid for arbitrarily large relative rotations and rotation rates. The nonlinear error dynamics for kinematics and the equation of motion is retained, yielding a tensor-based series solution for the Co-State as a function of error dynamics. Control sensitivity calculations are performed to handle model and parameter uncertainty in the real system. The OCEA (Object Oriented Coordinate Embedding) computational differentiation toolbox is used for automatically generating the first- through fourth-order partial derivatives required for the generalized control sensitivity differential equation. Several numerical examples are presented that demonstrate the effectiveness of the proposed approach. The methods presented are expected to be broadly useful for control applications in science and engineering. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL SOFTWARE

SESSION III

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

National Chairperson:	Jacob Griesbach Applied Defense Solutions
Local Chairpersons:	Cheryl Walker TASC, Inc.
	Reuben Rohrschneider Ball Aerospace & Technologies Corp.

The following paper numbers were not assigned:
AAS 13-038 to -040

UNDERSTANDING MODEL AND CODE BEHAVIOR FOR STATEFLOW CONSTRUCTS*

William B. Campbell,† Mike Anthony‡ and Becky Petteys§

Scheduling, supervisory logic, and fault management are often the most challenging components of a software design to develop, test, and verify. In a Model-Based Design process that leverages Simulink®, Stateflow® is regularly employed to mitigate these challenges. Its environment provides an infrastructure for developing state machines, truth tables, and flow charts. While such schematics are helpful in understanding complex logical systems, adopting a new modeling schema brings about its own difficulties. A variety of design patterns are available within Stateflow, but what is the precise behavior of a particular pattern, and which is the most desirable under a particular circumstance?

Common Stateflow design constructs are examined within this report. Fundamental architectural decisions such as state actions versus transition actions, events versus transition conditions, and MATLAB® versus C as the action language are explored by examining the performance of each construct. Behavior is studied within the Simulink model as well as the C code derived from Stateflow via Embedded Coder®. Each construct is vetted for consistency with existing Stateflow modeling standards such as the MathWorks Automotive Advisory Board Model Style Guide and the NASA Orion GN&C MATLAB and Simulink Standards. Results demonstrate that there is rarely an unequivocally superior design construct. However, architectures can be optimized based on specific software application, desired system behavior, and the developers' technical background. [View Full Paper]

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IMPACTS OF MICRO DEBRIS ON MICROSCOPE

Florence Génin[*] and Pascal Prieur[†]

MICROSCOPE is a mission whose main objective is to progress in fundamental physics by testing the Equivalence Principle with an accuracy of 10^{-15}. The scientific instrument is a differential electrostatic accelerometer developed by ONERA. The accelerometer is also part of the attitude and accelerations control system. Its high sensitivity enables a very accurate drag-free control. However, its reduced range of measure makes it vulnerable to parasite accelerations.

The population of debris on low Earth orbit keeps on increasing. Given the accelerometer accuracy of 1.10^{-12} m/s²/√Hz, a debris as small as 10^{-10}kg would disturb the measure. Therefore, micro debris impacts have to be taken into account as a new environmental perturbation. Compared to traditional AOCS continuous disturbances for which precise models are available, the stochastic non-stationary disturbances generated by micro debris impacts are more difficult to model and to analyze.

The paper presents the method used to estimate the debris flux on MICROSCOPE orbit and the consequences on the mission. Then it focuses on the strategy implemented to optimize the convergence time of the control loop of the acceleration and attitude control system after an impact. At the end, the conclusions are presented for Microscope and are extended to provide guidelines for future missions which, given the increasing sensitivity of payloads, might be confronted to the same issue.

[View Full Paper]

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AAS 13-033

SPACECRAFT DESIGN TOOL FOR PLUG-N-PLAY SATELLITE SIMULATION AND TEST BYPASS CONTROL

Jacob D. Griesbach,[*] Kyle Nave[†] and Tom Mann[‡]

Software plug-ins have been developed for the Spacecraft Design Tool (SDT) that enables SDT to communicate via SPA-S RMAP specifically for the Modular Space Vehicle (MSV) satellite program. This allows SDT to simulate MSV components that have not been physically incorporated yet and emulates associated messaging to test and analyze associated performance metrics. Via the same plug-ins, a test bypass (TB) infrastructure is also provided that allows SDT to *override* data written to/from supported spacecraft components in real-time. This allows the satellite to be spaceflight tested on a lab bench or during assembly in a high bay, with its components acting *as-if* they were in actual spaceflight. [View Full Paper]

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AAS 13-034

PARALLELIZED SIGMA POINT AND PARTICLE FILTERS FOR NAVIGATION PROBLEMS

Haijun Shen,[*] Vivek Vittaldev,[†] Christopher D. Karlgaard,[‡] Ryan P. Russell[§] and Etienne Pellegrini[**]

Advanced filters like the sigma point and particle filters are more accurate than the extended Kalman filter for nonlinear and non-Gaussian applications, but experience drawbacks such as being computationally expensive with a serial implementation. However, since the majority of the computation can be carried out simultaneously, these filters are inherently well suited for parallel computing. This research leverages inexpensive and personal-level parallel computing architectures, such as the NVIDIA Graphics Processing Units (GPUs) and multi-core CPUs to exploit such parallelism. In particular, parallelization of the Unscented Kalman filter (UKF) and the bootstrap Particle Filter (PF) applied to an orbit determination problem and a loosely coupled GPS/INS integration problem is the main objective of this work. This work demonstrates that the UKF and the PF can be applied to the two navigation problems with great benefits in the presence of nonlinearities and non-Gaussian noises. An 8-time speedup is achieved for both filters with an 8-thread CPU, and up to two orders of magnitude speedups are achieved using a M2090 GPU. The results show that the two UKF implementations can be executed in real time without parallelization, but the two PF implementations can be executed in real time only when parallelized on a GPU. [View Full Paper]

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AAS 13-035

A SURVEY OF SPACECRAFT JET SELECTION LOGIC ALGORITHMS*

David M. Shoemaker†

This paper presents a survey of jet selection logic algorithms that are found in software on existing and upcoming spacecraft. Three common algorithms that are evaluated in detail include various table-lookup implementations, pseudo inverse (least squares) formulations, and candidate optimal group (COG). The survey evaluates these algorithms against multiple criteria, including throughput and memory usage on embedded flight processor, flexibility to recover from a thruster fault, and propellant optimization. An evaluation of thruster firing authority and efficiency is discussed for representative thruster layouts. At the conclusion of the paper, the reader should be able to complete an algorithm trade study for a program's specific requirements and mission profile. [View Full Paper]

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AAS 13-036

CLOSED-LOOP TESTING OF THE ORION RENDEZVOUS GNC ALGORITHMS IN THE SPACE OPERATIONS SIMULATION CENTER

John A. Christian,* Christopher N. D'Souza,† Zoran Milenkovic‡ and Rebecca Johanning*

The Orion relative navigation team recently performed a series of closed-loop tests of the Orion rendezvous Guidance, Navigation, and Control (GNC) algorithms with sensor hardware-in-the-loop at the Lockheed Martin Space Operations Simulation Center (LM-SOSC). These tests used a Vision Navigation Sensor (VNS) Flash LIDAR to observe a high-fidelity mock-up of the International Space Station (ISS), while driving a large 6-DOF robot capable of simulating the closest 60 m of the rendezvous. Through this setup, the team was able to successfully demonstrate closed-loop performance of an autonomous rendezvous with a cooperative target in a realistic environment. This paper will provide a detailed discussion of the key flight software components, including: (1) the NASA-developed reflector finding, reflector identification/tracking, and pose algorithms; (2) the relative navigation extended Kalman Filter; and (3) the guidance algorithms for final approach. Important lessons-learned from this test campaign will also be documented. Finally, performance results from these closed loop runs will be provided.
[View Full Paper]

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SAFE HAVEN FOR AN INFRARED TELESCOPE IN LEO ORBIT (WISE Sun & Earth Pointing Prevention)

Martha Kendall*

The Wide-Field Infrared Survey Explorer (WISE) mission launched in December of 2009 is a true success story. The instrument had to be protected from infrared heat of the Sun and the Earth. To accommodate the requirement of keeping the Sun and Earth significantly away from the instrument boresight, there were large instrument keep-out zones. So large in fact, it is easier to describe them as keep-in zones. The algorithm to keep the Sun and Earth out of these zones and optimize the direction of travel to reduce risk of spending more time in the keep out zones was developed during Phase B. This algorithm was not only tested on the ground during Phase C/D but was intentionally exercised on-orbit in Phase E. The algorithm had to be developed because no previous Ball missions had both Sun and Earth Exclusion zones in quite the same way. Additionally, the Emergency Mode Controller (EMC), which could only do simple math functions, had to be able to implement Sun & Earth Pointing Prevention (SEPP). The mission performed beyond expectations on-orbit and never required the use of the algorithm; however, it was flight proven because in the commissioning phase ground ops intentionally commanded the instrument into the Earth Keep-out zone and the spacecraft responded to keep the instrument from entering it.

Keywords: WISE, algorithm, infrared, Sun Keep-out, Earth Keep-out, Sun & Earth Pointing Prevention. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL HARDWARE

SESSION IV

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

National Chairpersons:	Gianfranco Sechi ESA - ESTEC Neil Dennehy NASA Goddard Space Flight Center
Local Chairperson:	Daniel Motooka Lockheed Martin Space Systems

The following paper numbers were not assigned:

AAS 13-047 to -050

AAS 13-041

TURNKEY CMG-BASED MOMENTUM CONTROL FOR AGILE SPACECRAFT

Brian Hamilton*

Single-gimbal control moment gyroscopes (CMG) offer significantly greater vehicle acceleration (>100x) than a reaction wheel system of the same power. However, controlling an array of CMGs is a difficult task, with little practical help available in the open literature. Honeywell has developed turnkey controls for "roof" arrays of up to 6 CMGs that can be embedded in the array hardware or licensed separately. These controls accept a simple torque command, and provide deterministic, singularity-free operation with guaranteed torque availability. They also transparently manage CMG hardware failures, spin-up/down events, etc. without loss of control. This paper describes the use and sizing of CMG-based momentum systems using the Honeywell technology. [View Full Paper]

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DESIGN AND GROUND TEST RESULTS FOR THE LANDER VISION SYSTEM*

Andrew Johnson, Chuck Bergh, Yang Cheng, Dan Clouse, Kim Gostelow, Keizo Ishikawa, Anup Katake, Ken Klaasen, Milan Mandic, Mishrahim Morales, Sung Park, Al Sirota, Gary Spiers, Nikolas Trawny, John Waters, Aron Wolf, Jason Zheng and Will Zheng†

The Lander Vision System (LVS) is a tightly integrated bolt-on smart sensor system that provides real-time terrain relative position, velocity, attitude and altitude while also detecting landing hazards. The LVS can increase access to scientifically rich landing sites and is a low mass, volume and cost alternative to radar-based landing sensors. The LVS hardware fuses measurements from a visible camera, flash lidar and inertial measurement unit using a terrain relative navigation filter operating on a high performance compute element. This paper describes the design of an LVS prototype created from commercial components with a path to flight implementation and describes initial terrain relative navigation results produced on the computing hardware.
[View Full Paper]

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* This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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SINPLEX: A SMALL INTEGRATED NAVIGATION SYSTEM FOR PLANETARY EXPLORATION

Stephen R. Steffes,[1] Stephan Theil,[2] Michael Dumke,[3] David Heise,[3] Marco Sagliano,[3] Malak A. Samaan,[3] Erik Laan,[4] Murat Durkut,[5] Tom Duivenvoorde,[6] David Nijkerk,[7] Jan Schulte,[8] Stefan Söderholm,[9] Daniel Skaborn,[10] Joris Berkhout,[11] Marco Esposito,[12] Simon Conticello,[13] Richard Visee,[14] Bert Monna[15] and Frank Stelwagen[15]

SINPLEX is a research and development project funded by the European Commission. Its main goal is to develop an innovative solution to significantly reduce the mass of the navigation subsystem for exploration missions which include landing and/or rendezvous and capture phases. Future space missions which explore asteroids, comets, planets and planetary moons will likely bring robotic vehicles and may provide the capability to return samples to Earth. For these kinds of missions in particular, mass is one of the most critical factors. In SINPLEX, the system mass is reduced while still maintaining good navigation performance as compared to a conventional modular system. This is done by functionally integrating the navigation sensors, using micro- and nanotechnology to miniaturize electronics and fusing the sensor data within a navigation filter to improve navigation performance. The designed system includes a navigation computer, IMU, laser altimeter/range finder, star tracker and navigation camera and is fully redundant. The objectives of the project are to develop an integrated novel navigation system, produce a breadboard and demonstrate its performance in a hardware-in-the-loop test facility with realistic trajectories. This work provides an overview of the project and presents the current design and status. [View Full Paper]

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AAS 13-044

EUROPEAN CONTROL MOMENT GYROSCOPE: IN-ORBIT HERITAGE

Philippe Faucheux* **and Michel Privat†**

In the early 2000s, ASTRIUM SAS in collaboration with RCD (Rockwell Collins Deutschland GmbH) and with CNES (French Space Agency) and ESA (European Space Agency) support, has developed the CMG 15-45 S product to fulfil the need of high agility for the French earth observation satellite Pléiades. This was the first Control Moment Gyroscope developed in Europe for space application. Capacity of this CMG is of 15 Nms for the angular momentum and of 45 Nm for the output torque.

First flight models were delivered over years 2006 and 2007 and are perfectly operating in orbit since December 2011. A total of 12 models are in orbit (Pléiades HR 1A and 1B manufactured for the CNES and Spot 6 developed by Astrium).

After an overview on the CMG 15-45 S design and qualification status, this paper presents the observed in-orbit performances of the CMGs cluster. Adequate telemetries allow to observe main performances of the CMG and to access to technological data to check good behaviour of these equipments in orbit like pointing performances, stability of kinetic momentum, wheel friction torque or power consumption. Other performances cannot be directly measured with specific CMG telemetries, but can be observed through the general behaviour of the satellite, especially the low level of microvibration through the good stability of the line of sight and quality of the images.

[View Full Paper]

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15-70 NMS RANGE REACTION WHEELS PERFORMANCE AT MOOG BRADFORD

Erik J. van der Heide, Patrick van Put and Phuoc Le*

In August 2006 Moog Bradford acquired the Reaction Wheel Technology originating from Astrium Ltd. (Mechanisms Product Group, Stevenage). With a long and excellent track record, the series of wheels offers superior performance in terms of momentum storage, torque and wheel speed measurement and has excellent zero-crossing and micro vibration characteristics.

Moog Bradford has modernized the Reaction Wheel technology and achieved a qualified supplier status in 2010. The key assets of the design, the performance as well as a summary of the qualification tests are presented in this paper. An overview is presented on the current backlog of wheels, which is enabling high end scientific and earth observation missions, like Bepi-Colombo, Solar Orbiter, Sentinel-2, EarthCare. Recently, Moog Bradford wheels have been baselined for a highly demanding GEO mission: Meteosat Third Generation.

Two sets of toolboxes have been developed to monitor the health condition of reaction wheels and to accurately model torque noise and micro-vibration characteristics. These tools are developed for and employed to iterate with customers in order to assess stability performance for high end missions like Meteosat Third Generation, or EUCLID.

This paper depicts a complete overview of the Reaction Wheel family, focusing on momentum storage, torque capability and life test performance. [View Full Paper]

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AAS 13-046

HYDRA STAR TRACKER ON-BOARD SPOT-6

Damien Piot,[*] Lionel Oddos-Marcel,[*] Benoit Gelin,[*] Alain Thieuw,[†] Patrick Genty,[†] Pierre-Emmanuel Martinez[‡] and Stephen Airey[§]

This paper presents results from the multiple-head CMOS based sensor Star Tracker, HYDRA from Sodern, on-board SPOT-6 Spacecraft from Astrium. Data collected during the first months of the mission are analyzed and successfully compared to predicted performances from on ground test and simulations. Single head performances and fused quaternion performances are evaluated by PSD calculation with splitting into the different frequency classes (temporal NEA, HFSE and LFSE) and fit very well simulated values. The LFSE is found very low at 0.4 arcsec (3 sigma) on the 3 axis (fused data). Sun and Earth limb exclusion angles have been validated and the negligible impact on performances of the moon in the Field of View has been checked. Also robustness to kinematics up to 3°/s and 4°/s² has been successfully tested. The paper ends with star catalog checking, single star performances comparison with simulation and evaluation of quality index. [View Full Paper]

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HUMAN SPACEFLIGHT GUIDANCE, NAVIGATION AND CONTROL

SESSION V

The recent rise in interest for and development of commercial crew vehicles creates a new paradigm in which governmental and commercial entities must cooperate and sometimes compromise on operational and safety practices for human spaceflight. GN&C plays an essential role in both these factors. This session aims to draw upon the extensive experience of the Shuttle program and the International Space Station (ISS), as well as explore new and innovative GN&C concepts applied to human spaceflight. Topics focus on level of automation for human spaceflight GN&C vs human-in-the-loop, recent experiences with commercial vehicles (crewed/non-crewed) requiring to dock with the ISS, commercial crew vehicle GN&C design and other related topics.

National Chairpersons:	Douglas Zimpfer Charles Stark Draper Laboratory
	Jack Brazzel NASA Johnson Space Center
Local Chairpersons:	Laura Brower Ball Aerospace & Technologies Corp.
	Jeff Parker University of Colorado

The following paper numbers were not assigned:

AAS 13-057 to -060

AAS 13-051

CONTROL REQUIREMENTS TO SUPPORT MANUAL PILOTING CAPABILITY

Nujoud Merancy, Kay Chevray, Rodolfo Gonzalez, Jennifer Madsen and Pete Spehar*

The manual piloting requirements specified under the NASA Constellation Program involved Cooper-Harper ratings, which are a qualitative and subjective evaluation from experienced pilots. This type of verification entails a significant investment of resources to assess a completed design and is not one that can easily or meaningfully be applied upfront in the design phase. The evolution of the Multi-Purpose Crew Vehicle Program to include an independently developed propulsion system from an international partner makes application of Cooper-Harper based design requirements inadequate.

To mitigate this issue, a novel solution was developed to reformulate the necessary piloting capability into quantifiable requirements. A trio of requirements was designed which specify control authority, precision, and impulse residuals enabling propulsion design within specified guidance and control boundaries. These requirements have been evaluated against both the existing Orion design and the proposed ESA design and have been found to achieve the desired specificity. The requirement set is capable of being applied to the development of other spacecraft in support of manual piloting.
[View Full Paper]

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AAS 13-052

ATLAS V EVOLUTION FOR HUMAN SPACEFLIGHT

John G. Reed* and Rick A. Mingee†

Since the 2011 selection of Atlas V as the launch vehicle for both the Boeing CST-100 and the Sierra Nevada Corporation (SNC) Dream Chaser® spacecraft, work has continued on the path to human rate the Atlas V launch vehicle. In September of 2011 ULA completed the Design Equivalency Review, a rigorous assessment of the flight-proven Atlas V launch vehicle's compliance with NASA human spaceflight requirements. In December 2011, ULA completed the Tailored Systems Requirements Review where the team reviewed the detailed evidence that demonstrates how the existing, flight-proven Atlas V meets the intent of NASA's Human Spaceflight Certification requirements. In April 2012, ULA announced the formation of the new Human Launch Services organization, dedicated to supporting NASA and its partners in the development of capabilities to deliver U.S. astronauts to Low Earth Orbit and human exploration beyond Earth orbit. In June of 2012 ULA conducted the System Requirements Review (SRR) and Systems Design Review (SDR), a multi-disciplined technical review that ensured the Atlas V system can proceed into the detailed design and development phase to provide launch services for NASA's commercial human spaceflight needs. These efforts culminated in Commercial Crew Integrated Capability Contract (CCICap) awards to both Boeing and SNC.

This paper discusses the efforts that have led us to the doorstep of this new phase in human access to space. We describe the launch vehicle aspects of CCICap, completion of the designs of the Emergency Detection System (EDS) and the Dual Engine Centaur (DEC), and the planning for launch site accommodations. Finally, we summarize the commercial crew path forward to renewed, US based, human-access to space. [View Full Paper]

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AAS 13-053

SUPPORTING CREWED LUNAR EXPLORATION WITH LIAISON NAVIGATION

Jason M. Leonard,[*] Jeffrey S. Parker,[†] Rodney L. Anderson,[‡] Ryan M. McGranaghan,[*] Kohei Fujimoto,[*] and George H. Born[§]

This paper examines the benefits of navigating a crewed vehicle between the Earth and the Moon using both ground tracking and satellite-to-satellite tracking. Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) is a new technique that has been shown to dramatically improve the navigation of lunar satellites, libration orbiters, and Earth orbiting satellites using scalar intersatellite observations. In this paper, LiAISON is applied to the problem of navigating a crewed vehicle to the Moon. It has been found that LiAISON observations improve the navigation accuracy enough to reduce the number of active ground tracking stations from six to three. [View Full Paper]

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OPTIMAL RECURSIVE DIGITAL FILTERS FOR ACTIVE BENDING STABILIZATION

Jeb S. Orr*

In the design of flight control systems for large flexible boosters, it is common practice to utilize active feedback control of the first lateral structural bending mode so as to suppress transients and reduce gust loading. Typically, active stabilization or phase stabilization is achieved by carefully shaping the loop transfer function in the frequency domain via the use of compensating filters combined with the frequency response characteristics of the nozzle/actuator system. In this paper we present a new approach for parametrizing and determining optimal low-order recursive linear digital filters so as to satisfy phase shaping constraints for bending and sloshing dynamics while simultaneously maximizing attenuation in other frequency bands of interest, e.g. near higher frequency parasitic structural modes. By parametrizing the filter directly in the z-plane with certain restrictions, the search space of candidate filter designs that satisfy the constraints is restricted to stable, minimum phase recursive low-pass filters with well-conditioned coefficients. Combined with optimal output feedback blending from multiple rate gyros, the present approach enables rapid and robust parametrization of autopilot bending filters to attain flight control performance objectives. Numerical results are presented that illustrate the application of the present technique to the development of rate gyro filters for an exploration-class multiengined space launch vehicle.

[View Full Paper]

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AAS 13-055

CAPABILITIES AND DEVELOPMENT OF DREAM CHASER SPACE VEHICLE

Ernest E. Lagimoniere Jr.,* Russell D. Howard† and I. T. Mitchell‡

This paper provides an overview of the capabilities and development of the Dream Chaser space vehicle and its Guidance Navigation and Control (GN&C) system design. The Dream Chaser is the only contender in the Commercial Crew Integrated Capability (CCiCap) program making use a lifting body vehicle and the GN&C system is being designed to take full advantage of its benefits. With lessons learned from previous lifting body programs the GN&C design will provide a level of robustness, capability and safety unequaled in human space flight to date. New technologies will be fully taken advantage of to increase performance capability and safety while concurrently employing tried and true technologies and algorithms to leverage a strong heritage of human spaceflight qualified GN&C design. Automatic control capability will be available throughout nearly the entire mission with primary manual mode control anticipated for key safety critical phases. [View Full Paper]

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AAS 13-056

THE RENDEZVOUS MONITORING DISPLAY CAPABILITIES OF THE RENDEZVOUS AND PROXIMITY OPERATIONS PROGRAM

**Christopher W. Foster,* Jack P. Brazzel,† Peter T. Spehar,†
Fred D. Clark‡ and Erin Eldridge§**

The Rendezvous and Proximity Operations Program (RPOP) is a laptop computer-based relative navigation tool and piloting aid that was developed during the Space Shuttle program. RPOP displays a graphical representation of the relative motion between the target and chaser vehicles in a rendezvous, proximity operations and capture scenario. After being used in over 60 Shuttle rendezvous missions, some of the RPOP display concepts have become recognized as a minimum standard for cockpit displays for monitoring the rendezvous task. To support International Space Station (ISS) based crews in monitoring incoming visiting vehicles, RPOP has been modified to allow crews to compare the Cygnus visiting vehicle's onboard navigated state to processed range measurements from an ISS-based, crew-operated Hand Held Lidar sensor. This paper will discuss the display concepts of RPOP that have proven useful in performing and monitoring rendezvous and proximity operations. [View Full Paper]

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POSITIONING, NAVIGATION AND TIMING

SESSION VI

Positioning, Navigation, and Timing (PNT) Assurance has become an important issue. Dependencies on PNT systems, such as the Global Positioning System (GPS) and other Global Navigation Satellite Systems (GNSS), are prolific throughout government, commercial business, and society today. GPS revolutionized military and commercial business, affecting everything from aviation flight safety and spacecraft, to cell phone technology and automobile navigation, to ship navigation and container tracking, to banking industry and cyber transactions. Assuring access to PNT has become a focus as threats to the signal environment increase. These threats range from unintentional threats of overuse of the spectrum where spread spectrum GNSS signals reside, to intentional threats from hostile jammers. Recent broadband initiatives by the U.S. Government and LightSquared to look at licensing adjacent spectrum brought about considerable controversy regarding the assurance of PNT spectrum. This unclassified session is intended to discuss, from all perspectives, the lessons learned, applied design improvements and considerations towards assuring the viability of PNT in the present future. Open for discussion are (1) assurance mitigation strategies by the GPS/DoD for PNT delivery including new capabilities and signals, (2) possible new standards for future receiver development, and (3) user end receiver, filter, and antenna advances in GNSS technology to mitigate issues arising from a less quiet spectrum in the future.

National Chairpersons:

Darrell Zimbleman
U.S Department of the Air Force

Mike Moreau
NASA Goddard
Space Flight Center

Local Chairpersons:

Lee Barker
Lockheed Martin Space Systems

Shawn McQuerry
Lockheed Martin Space Systems

The following paper was not available for publication:

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The following paper numbers were not assigned:

AAS 13-065 to -070

AAS 13-061

FIRST USE OF GLOBAL POSITIONING SYSTEM METRIC TRACKING FOR LAUNCH VEHICLE TRACKING

John G. Reed,* Ted Moore† and Hanchu Li‡

With the launch of the Atlas L-36 mission, the second certification flight of the GPS-MT system has been accomplished. After a brief review of the GPS-MT system, this paper discusses the certification efforts. We present an overview of the various approaches taken for certification. A summary of the resulting performance of the system follows. A discussion of the progress/status of the certification progress through the Oct 4th Delta IV 1st certification flight is provided. The conclusion covers the state of the operational system and the forward path for EELV range safety operations.

[View Full Paper]

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GOES-R USE OF GPS AT GEO (VICEROY-4)*

Stephen Winkler,† Chuck Voboril,† Roger Hart‡ and Mike King‡

Geostationary Operational Environmental Spacecraft-R Series (GOES-R) is the next generation of geostationary weather spacecraft and is scheduled for launch in 2015. The GOES-R spacecraft is 3-axis stabilized and designed for a minimum 15-year mission life. This spacecraft must operate through periodic station-keeping and momentum adjust maneuvers in order to facilitate near-continuous instrument observations. The down time requirement of under 120 minutes/year is nearly two orders of magnitude tougher than specified on previous missions. The addition of a GPS receiver and antenna system are key to achieving these goals. Highlights of this paper: (1) Architectural modifications to the Viceroy GPS receiver hardware and software enabling near 100% availability of navigation and timing data through periodic station-keeping maneuvers. (2) Antenna and receiver modifications for a GEO signal environment characterized by signals with low geometrical visibility/availability and high path loss. (3) GEO space qualification methodology, and (4) Actual test results. [View Full Paper]

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WORST-CASE GPS CONSTELLATION FOR TESTING NAVIGATION AT GEOSYNCHRONOUS ORBIT FOR GOES-R[*]

Kristin Larson,[†] Dave Gaylor[‡] and Stephen Winkler[§]

The Geostationary Operational Environmental Satellite – R Series (GOES-R) is the next generation NOAA weather satellite to be launched in 2015. GOES-R will use an L1 C/A GPS receiver (GPSR) to receive both GPS main beam and side lobe signals. The quality and availability of GPS signals at geosynchronous orbit (GEO) strongly impact navigation accuracy. For the GOES-R program, navigation accuracy requirements must be maintained during nominal operation of the spacecraft including station-keeping maneuvers. The GPSR solution 3-sigma accuracy requirement in position knowledge is 75 meters for the in-track and cross-track directions, and 100 meters for radial direction. Since maneuvers are not modeled in the onboard GPSR software, accuracy can degrade significantly during a maneuver. In order to verify that the GOES-R GPS navigation system can meet the stringent accuracy requirements during station-keeping maneuvers, a worst-case test scenario was developed for receiver testing. To find this scenario, we developed a simulation that models the GPS constellation and a GPS receiver and determines whether each GPS space vehicle (SV) can be tracked based on a high fidelity link budget model. Using this simulation, we modified the position of the GPS constellation relative to the Earth to find the scenario with the fewest number of trackable SVs during a North-South stationkeeping maneuver. The lowest visibility cases were found to be dependent on the right ascension, and occurred at 6 different shifts in right ascension. GPS receiver results from the Engineering Development Unit (EDU) are provided for both nominal and worst-case performance. [View Full Paper]

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ENTRY, DESCENT AND LANDING FLIGHT DYNAMICS

SESSION VII

The process of getting a spacecraft safely from the top of a planetary body's atmosphere to the surface is often one of the most challenging aspects of a given mission. Many factors must be accounted for including extreme heating environments, high deceleration loads, stability throughout many aerodynamic regimes, and landing site targeting. Demands for higher entry masses and velocities have continually pushed the envelope of our EDL capabilities, making this a very dynamic and interesting field. This session will explore the challenges of entry, descent, and landing by examining recent EDL experiences as well as current and future advancements in EDL strategies and technology.

National Chairperson: Steve Lee, NASA Jet Propulsion Laboratory

Local Chairpersons: Scott Francis, Lockheed Martin Space Systems

Paul Graven, Cateni

The following papers were not available for publication:

AAS 13-071
(Paper Withdrawn)
AAS 13-075
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 13-079 to -080

BLUNT BODY DYNAMIC STABILITY DURING PARACHUTE REEFING STAGES*

Michael P. Hughes† and Joe D. Gamble‡

Dynamic stability of blunt entry bodies is an area of ongoing research. Predictive knowledge of dynamic stability is critical to entry, descent and landing system design in that it allows the engineer to balance risk and performance in designing final staging events, primarily parachute deployments. The parachutes themselves, change the dynamics of the vehicle and thus dynamic stability. There may be several reefed stages, as in Apollo and Orion MPCV, that change the dynamics in a time varying way. In this paper, we present a closed form method to calculate the damping ratio and natural frequency for a system with multiple reefed stages, a way to bound the pitch motion evolution for this system, and provide insight into the design and environmental parameters that drive stability. Examples from Apollo parachute drop tests are included to anchor the analysis. [View Full Paper]

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AAS 13-073

COMPARISON OF REVISED APOLLO FINAL PHASE REFERENCE EQUATIONS OF MOTION

Scott Jenkins,[*] Thomas Fill[†] and Stephen Thrasher[‡]

The Apollo Entry Guidance Final Phase has been used successfully for such missions as Apollo, Mars Science Laboratory (MSL), and will be used as the backbone of PredGuid the entry guidance algorithm for the Orion Exploration Flight Test 1 (EFT-1), the first flight test of the Orion GNC FSW. The Apollo Final Phase is a simple reference following guidance scheme, which was formulated with several assumptions. These assumptions lead to differences between the true dynamics of the vehicle during entry and the estimated dynamics used to generate the reference trajectory use by the guidance algorithm to calculate a desired bank angle. To obtain acceptable results from guidance, heuristically applied "Kentucky Windage" is generally used in the design of the reference trajectory. This paper seeks to outline improvements to the dynamics used in the design of the reference trajectory by eliminating the Apollo era simplifying assumptions and investigate how these modeling improvements can lead to satisfactory reference trajectory design with a more model based approach without heuristic adjustments. Improvements in the predicted trajectory are discussed, as well as closed loop Monte-Carlo analysis. [View Full Paper]

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AAS 13-074

DESCENT AND LANDING TRIGGERS FOR THE ORION MULTIPURPOSE CREW VEHICLE EXPLORATION FLIGHT TEST-1

Brian D. Bihari,[*] Charity J. Duke[†] and Jeffrey D. Semrau[‡]

The Orion Multi-Purpose Crew Vehicle (MPCV) will perform a flight test known as Exploration Flight Test-1 (EFT-1) currently scheduled for 2014. One of the primary functions of this test is to exercise all of the important Guidance, Navigation, Control (GN&C), and Propulsion systems, along with the flight software for future flights. The Descent and Landing segment of the flight is governed by the requirements levied on the GN&C system by the Landing and Recovery System (LRS). The LRS is a complex system of parachutes and flight control modes that ensure that the Orion MPCV safely lands at its designated target in the Pacific Ocean. The Descent and Landing segment begins with the jettisoning of the Forward Bay Cover and concludes with sensing touchdown. This paper discusses the requirements, design, testing, analysis and performance of the current EFT-1 Descent and Landing Triggers flight software.
[View Full Paper]

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ADAPT – A CLOSED-LOOP TESTBED FOR NEXT-GENERATION EDL GN&C SYSTEMS*

MiMi Aung,† Behçet Açıkmeşe,‡ Andrew Johnson,* Martin Regehr,* Jordi Casoliva,* Swati Mohan,* Aron Wolf,* Daniel Scharf,* Homayoon Ansari,* David Masten,§ Joel Scotkin** and Scott Nietfeld**

A next-generation Mars landing goal is precise and safe landing with less than 1 km uncertainty to reach targets of scientific interest within hazardous terrain. This goal can be achieved by enhancing the SkyCrane Entry, Descent and Landing (EDL) architecture debuted successfully by the Mars Science Laboratory [1], by adding: (i) Terrain Relative Navigation (TRN) during the parachute phase to determine the vehicle position and attitude relative to the landing site; (ii) capability to maneuver the spacecraft to reach the exact target site, requiring a course correction of multiple kilometers during the powered descent phase; and (iii) Hazard Detection and Avoidance (HDA) in the landing area [2]. JPL is developing key technologies to enable such landings at Mars, including Guidance for Fuel-Optimal Large Divert (G-FOLD) [3][4], a trajectory optimizer suitable for on-board execution, and the Mars Lander Vision System (LVS) [5] for TRN and hazard detection. Reliable operation at Mars necessitates earth-based, end-to-end closed loop testing of these technologies as an integrated system. ADAPT (Autonomous Ascent and Descent Powered-Flight Testbed) is a testbed for this purpose. In ADAPT, JPL Mars Lander Vision System and a payload computer will be integrated into the Xombie vehicle built by Masten Space Systems, Inc. In flight, the JPL payload will perform TRN, and execute G-FOLD [6] to calculate a fuel-optimal trajectory to the landing site. The Xombie vehicle will follow the trajectory to the landing site. System engineering is performed collaboratively by JPL and Masten Space Systems, Inc. We began ADAPT development by first flying with Xombie three Mars-representative large-divert trajectories generated before launch using G-FOLD. This first phase was highly successful. The Xombie vehicle diverted 750-m laterally during descent from 500-m initial altitude with high precision and set a new record for the lateral flight distance performed by a vertical-take-off-vertical-landing vehicle, and set new altitude and distance records for Xombie vehicle. In upcoming flights, we will continue to add features to the testbed and demonstrate a fully autonomous Mars-like precise and safe landing with TRN, G-FOLD and HDA. This paper details the ADAPT testbed design and the planned set of experiments. [View Full Paper]

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AAS 13-077

ATTITUDE CONTROL PERFORMANCE OF IRVE-3

Robert A. Dillman,[*] Valerie T. Gsell[†] and Ernest L. Bowden[†]

The Inflatable Reentry Vehicle Experiment 3 (IRVE-3) launched July 23, 2012, from NASA Wallops Flight Facility and successfully performed its mission, demonstrating both the survivability of a hypersonic inflatable aerodynamic decelerator in the reentry heating environment and the effect of an offset center of gravity on the aeroshell's flight L/D. The reentry vehicle separated from the launch vehicle, released and inflated its aeroshell, reoriented for atmospheric entry, and mechanically shifted its center of gravity before reaching atmospheric interface. Performance data from the entire mission was telemetered to the ground for analysis. This paper discusses the IRVE-3 mission scenario, reentry vehicle design, and as-flown performance of the attitude control system in the different phases of the mission. [View Full Paper]

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AAS 13-078

THE MARS SCIENCE LABORATORY (MSL) ENTRY, DESCENT AND LANDING INSTRUMENTATION (MEDLI): HARDWARE PERFORMANCE AND DATA RECONSTRUCTION

Alan Little,[*] Deepak Bose,[†] Chris Karlgaard,[‡] Michelle Munk,[*] Chris Kuhl,[*] Mark Schoenenberger,[*] Chuck Antill,[*] Ron Verhappen,[‡] Prasad Kutty[§] and Todd White[**]

The Mars Science Laboratory (MSL) Entry, Descent and Landing Instrumentation (MEDLI) hardware was a first-of-its-kind sensor system that gathered temperature and pressure readings on the MSL heatshield during Mars entry on August 6, 2012. MEDLI began as challenging instrumentation problem, and has been a model of collaboration across multiple NASA organizations. After the culmination of almost 6 years of effort, the sensors performed extremely well, collecting data from before atmospheric interface through parachute deploy. This paper will summarize the history of the MEDLI project and hardware development, including key lessons learned that can apply to future instrumentation efforts. MEDLI returned an unprecedented amount of high-quality engineering data from a Mars entry vehicle. We will present the performance of the 3 sensor types: pressure, temperature, and isotherm tracking, as well as the performance of the custom-built sensor support electronics. A key component throughout the MEDLI project has been the ground testing and analysis effort required to understand the returned flight data. Although data analysis is ongoing through 2013, this paper will reveal some of the early findings on the aerothermodynamic environment that MSL encountered at Mars, the response of the heatshield material to that heating environment, and the aerodynamic performance of the entry vehicle. The MEDLI data results promise to challenge our engineering assumptions and revolutionize the way we account for margins in entry vehicle design. [View Full Paper]

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GUIDANCE, NAVIGATION, AND CONTROL BEYOND 2022

SESSION VIII

Order of magnitude improvements in the 2022 and beyond timeframe for guidance, navigation and control. Papers are solicited to discuss novel technologies and approaches that offer significant improvements over current systems in future decades. These can include new sensor technologies for star trackers, gyros, and accelerometers; new actuator technologies for momentum exchange devices, fast steering mirrors, and electric propulsion systems; new approaches to data fusion in order to estimate platform position, velocity and orientation; new applications for these improvements as well as challenging future environments such as GPS-denied conditions. Papers should concentrate on developments that are feasible in the 2022 and beyond timeframe

National Chairperson: Bradley Moran
C. S. Draper Laboratory

Local Chairpersons: Kyle Miller
Ball Aerospace & Technologies Corp.

Michael Epstein
Lockheed Martin Space Systems

The following papers were not available for publication:

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(Paper Withdrawn)

AAS 13-087
(Paper Withdrawn)

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AAS 13-088 to -090

THE FUTURE OF TIME DOMAIN SWITCHED (TDS) INERTIAL SENSORS AS AN ENABLER FOR NEXT GENERATION MISSIONS

Darren D. Garber,* Matthew E. Wimmer,†
Mark Fralick‡ and Richard L. Waters§

MEMS inertial sensors are on the cusp of reaching performance levels that will provide the transformative capabilities necessary to revolutionize the autonomy, navigation and control of spacecraft. The low power, enhanced resolution and superior long term stability of next generation devices will not only enable new missions but also provide an order of magnitude improvement to existing missions. The performance of these devices will provide new and unique measurements to navigation and attitude determination filters to allow for precision maneuver control and reconstruction, open loop slewing, direct sensing of the perturbing environment, redundant attitude knowledge, transforming the vehicle into a gyro and in the extreme, enabling gravity gradient navigation. In each case the fundamental metrology provided by these sensors allows for increased mission availability, improved state knowledge and enhanced collection opportunities. [View Full Paper]

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THE ROLE OF X-RAYS IN FUTURE SPACE NAVIGATION AND COMMUNICATION*

Luke M. B. Winternitz,† Keith C. Gendreau,‡ Munther A. Hassouneh,§ Jason W. Mitchell, Wai H. Fong,†† Wing-Tsz Lee,‡‡ Fotis Gavriil§§ and Zaven Arzoumanian***

In the near future, applications using X-rays will enable autonomous navigation and time distribution throughout the solar system, high capacity and low- power space data links, highly accurate attitude sensing, and extremely high- precision formation flying capabilities. Each of these applications alone has the potential to revolutionize mission capabilities, particularly beyond Earth orbit. This paper will outline the NASA Goddard Space Flight Center vision and efforts toward realizing the full potential of X-ray navigation and communications. [View Full Paper]

 Funding provided by NASA STP/GCD and GSFC/OCT.

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DRAPER PERSPECTIVE ON FUTURE GN&C*

Marvin A. Biren, Megan L. Mitchell and Bradley A. Moran†

From its position as a leader in the development of Inertial Guidance for over 60 years, Draper Laboratory presents its view of the status of current trends in GN&C development, the probable course of development over the next 10 years, and possible goals for further development beyond. This perspective includes a summary of current inertial component applications and performance, and discussion of current leading trends in conventional, MEMS and advanced inertial instruments. The trade-offs of the utility and cost of external aids, such as stellar sightings and GPS are discussed, as is the range of options for operation in a GPS-challenged or -denied environment. Missions for remote or autonomously guided vehicles will become more complex in the next 10 years, and the character of GN&C will change accordingly.

General Disclaimer: All predictions of the future are rendered obsolete on the telling, and will appear naïve in ten years time. [View Full Paper]

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AAS 13-085

FAST STEERING MIRRORS FOR SPACECRAFT SLEW, SETTLE, AND TRACKING PERFORMANCE ENHANCEMENT

Tae W. Lim*

Approaches to harness recent advances in capabilities of a fast steering mirror (FSM) in its size, range of motion, and control bandwidth are explored to enhance the slew, settle, and jitter suppression performance of optical telescope assembly (OTA) payloads as well as their host satellites. As a point study to assess the slew and settle performance benefits of using FSMs and to study their integration approaches for a satellite hosting an OTA payload, the step-stare observation of the Joint Milli-Arcsecond Pathfinder Survey (JMAPS) mission was considered in this paper. The first approach studied was to install an FSM in front of the OTA to perform the step-stare operation by steering the FSM without maneuvering the host satellite. The second approach was to use the satellite bus and its attitude control system to perform slews while employing the FSM to improve settling performance after the slew. The first approach was effective in reducing slew and settle duration, which may take up a significant portion in time in the step-stare observation sequence. However, it required a sizeable FSM mirror with a large range of motion capability in order to accommodate the OTA aperture size. The second approach was beneficial in reducing the required size and range of motion of the FSM by allowing the integration of the FSM within the OTA but was not as effective in reducing the slew and settle time as the first approach since the slew was conducted by the satellite bus. Although preliminary in nature, this study supports that FSMs can be an effective alternative to improving agility and pointing stability for future satellites hosting OTA payloads. [View Full Paper]

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AAS 13-086

NAVIGATION AND MISSION DESIGN TECHNOLOGIES FOR FUTURE PLANETARY SCIENCE MISSIONS*

Lincoln J. Wood,† Shyam Bhaskaran,‡ James S. Border,§ Dennis V. Byrnes, Laureano A. Cangahuala,†† Todd A. Ely,† William M. Folkner,† Charles J. Naudet,‡‡ William M. Owen,‡ Joseph E. Riedel,§§ Jon A. Sims,‡ and Roby S. Wilson‡**

Future planetary explorations envisioned by the National Research Council's *Vision and Voyages for Planetary Science in the Decade 2013–2022* seek to reach targets of broad scientific interest across the solar system. Advancements in guidance, navigation, and control and mission design—ranging from software and algorithm development to new sensors—will be necessary to enable these future missions. This paper describes the general categories of mission design capabilities that need further development in support of future planetary science missions: multiple-encounter tour design, close-proximity trajectory design for small-body missions, low-energy trajectory design and optimization, multiple-spacecraft trajectory optimization, and low-thrust trajectory design and optimization. The paper also describes a number of ways in which deep space navigation may be enhanced in the future, including precise one-way radio metric tracking, based on use of the proposed Deep Space Atomic Clock; autonomous navigation (in particular, its application to autonomous aerobraking, outer planet tours, and primitive body/lunar proximity operations and pinpoint landing); evolutionary improvements in Deep Space Network radio metric data accuracy; and derivation of metric tracking data from optical communication links. [View Full Paper]

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GUIDANCE, NAVIGATION AND CONTROL OPERATIONS AROUND ASTEROIDS AND COMETS

SESSION IX

Over the last two decades, multiple countries have engaged on missions to develop and fly spacecraft that explore small solar system bodies, including asteroids and comets. These efforts have revealed successful approaches and operational challenges for GNC around small bodies. Robust GNC includes mission design and autonomy to accommodate long round-trip light times, chaotic trajectories around distended shapes, precision navigation accuracies to meet science data needs, and spacecraft control when contacting a surface. Through participation of NASA, JAXA, and ESA representatives, this session will provide a setting for international collaboration to explore the progress in trying to meet these challenges, paving the way for future success in humankind's exploration of asteroids and comets.

National Chairperson: Dan Scheeres, University of Colorado

Local Chairpersons: Christy Edwards-Stewart, Lockheed Martin Space Systems

Alex May, Lockheed Martin Space Systems

The following paper numbers were not assigned:

AAS 13-098 to -100

AAS 13-091

ROSETTA COMET MISSION: CLOSE PROXIMITY OPERATIONS AT COMET 67P/CHURYUMOV-GERASIMENKO AND LANDING PHILAE

Jens Biele,[*] Stephan Ulamec,[*] Eric Jurado,[†] Elisabet Canalias,[†] Alejandro Blazquez,[†] Thierry Martin,[†] Björn Grieger[‡] and Michael Küppers[‡]

The first ever dedicated comet Lander is Philae, an element of ESA´s Rosetta mission to comet 67P/Churyumov-Gerasimenko. Rosetta was launched in 2004. After about 7 years of interplanetary cruise (including three Earth and one Mars swing-by as well as two asteroid flybys) the spacecraft went into a deep space hibernation in June 2011. When approaching the target comet in early 2014, Rosetta is re-activated. The cometary nucleus will be characterized remotely to prepare Lander delivery, currently foreseen for November 2014. Comet escort by the spacecraft will continue until end 2015, beyond the peak comet activity at perihelion.

In contrast to small body flyby missions (e.g., the Giotto mission to Halley's comet in 1986), Rosetta will actually orbit or "quasi-orbit" the comet nucleus, being inside it's Hill sphere. We discuss spacecraft navigation issues, comet characterization, the landing site selection process and Lander delivery. [View Full Paper]

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AAS 13-092

ADVANCED GNC TECHNOLOGIES FOR PROXIMITY OPERATIONS IN MISSIONS TO SMALL BODIES

P. J. Llanos,[*] M. Di Domenico[†] and J. Gil-Fernandez[‡]

An assessment of the descending and landing phase of Marco Polo R and OSIRIS-REx missions is performed. A touch-and-go strategy has been analyzed for both scenarios on two distinct target asteroids with different landing requirements. In addition a full landing with different requirements is also evaluated. The comparison of the different scenarios is done with Monte Carlo analyses using the GNC system and the MIL simulator developed for the previous Marco Polo mission. The result of these analyses is the first step in the research to improve and optimize the GNC equipment, strategy and algorithms for the proximity operations of missions to asteroids.
[View Full Paper]

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AAS 13-093

GNC FOR MARCO POLO-R AND MOONS OF MARS SAMPLE RETURN MISSIONS: SYSTEM DESIGN, CRITICAL TECHNOLOGIES AND SYNERGY

Daniele Gherardi,[*] David Agnolon,[†] Denis Rebuffat,[†] Marc Chapuy,[‡] Ferdinando Cometto,[§] Lisa Peacocke,[**] Gino Bruno Amata,[††] Francesco Cacciatore[‡‡] and Sandie Deslous[§§]

The European Space Agency (ESA) roadmap towards exploration of small solar system bodies includes the Rosetta mission, currently on its way to a comet and two asteroid sample return mission studies: Marco Polo-R (MP-R) and Moons of Mars Sample Return (MMSR), also known as Phootprint. This paper focuses on MP-R and MMSR. MP-R is being studied in the frame of the Cosmic Vision ESA Science Programme whereas MMSR is studied in the frame of the Mars Robotic Exploration Programme. Several critical technologies are similar between these two mission concepts and in particular the Guidance, Navigation and Control (GNC) aspects including the guidance strategy, the use of relative vision-based navigation, and the proximity and landing operations. This paper discusses the overall design constraints; architecture and performances assessment achieved by the GNC subsystem for both of these sample return mission concepts. ESA initiated both study activities in the Concurrent Design Facility (CDF) followed by parallel system assessment studies, led by two industrial teams as well as set of technology-focused activities bringing about the various critical elements to the appropriate maturity level. Sample return missions are demanding from a GNC perspective. The most critical phase deals with the proximity operations around the small body and more particularly, with the descent and landing (D&L) phase during which the samples to be returned to the Earth are collected. The actual landing accuracy requirement for these two ESA missions is aimed to be in the order of tens or hundreds of meters, depending on the small body size, using visual based techniques as main D&L navigation aid. [View Full Paper]

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AAS 13-094

GUIDANCE, NAVIGATION AND CONTROL OF HAYABUSA2 IN PROXIMITY OF AN ASTEROID*

Fuyuto Terui,† Naoko Ogawa,† Yuya Mimasu,†
Seiji Yasuda‡ and Masashi Uo‡

Japan Aerospace Exploration Agency (JAXA) is now in the course of production of a deep space asteroid exploration spacecraft “Hayabusa2” which is planned to be launched in 2014 as a follow on from “Hayabusa.” The planned operations of Hayabusa2 in proximity of an Asteroid are almost similar to the ones of Hayabusa but there are some new operations such as releasing an explosive called “impactor” in order to make a crater on the surface of the asteroid and “pinpoint touchdown” to the newly created crater in order to get “fresh” material underneath the surface of it.

GN&C for proximity flight of Hayabusa2 around the asteroid is planned to be performed by switching “ground station based navigation and guidance operation” and “onboard autonomous navigation and control” depending on the distance from the asteroid.

This paper explains image-based navigation, guidance and control strategy based on the ground station operation with round-trip time delay mainly for approach phase to the asteroid and autonomous six degree-of-freedom (position and attitude) control algorithm mainly for final approach and touchdown to the surface of the asteroid.

[View Full Paper]

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† Japan Aerospace Exploration Agency (JAXA), Japan.

‡ NEC Corporation, Japan.

AAS 13-095

OSIRIS-REX TOUCH-AND-GO (TAG) MISSION DESIGN AND ANALYSIS

Kevin Berry,[*] Brian Sutter,[†] Alex May,[‡] Ken Williams,[§] Brent W. Barbee,[**] Mark Beckman[††] and Bobby Williams[‡‡]

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission is a NASA New Frontiers mission launching in 2016 to rendezvous with the near-Earth asteroid (101955) 1999 RQ36 in late 2018. After several months in formation with and orbit about the asteroid, OSIRIS-REx will y a Touch-And-Go (TAG) trajectory to the asteroid's surface to obtain a regolith sample. This paper describes the mission design of the TAG sequence and the propulsive maneuvers required to achieve the trajectory. This paper also shows preliminary results of orbit covariance analysis and Monte-Carlo analysis that demonstrate the ability to arrive at a targeted location on the surface of RQ36 within a 25 meter radius with 98.3% confidence. [View Full Paper]

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AAS 13-096

SPACECRAFT REORIENTATION CONTROL ANALYSIS FOR TOUCH-AND-GO COMET SAMPLE RETURN

Jack Aldrich,[*] David Bayard[*] and Milan Mandić[*]

This article revisits the large-angle spacecraft reorientation attitude control problem from the perspective of maximizing the disturbance rejection capacity with respect to the maneuver time. To ensure stable reorientation, a smooth attitude trajectory command is profiled to match the estimated initial state and the desired final state of the spacecraft; with command following provided by state-feedback control. In this setting, the closed-loop tracking error dynamics are shown to belong to a class of nonlinear systems consisting of nominal linear time-varying system plus a set of structured time-varying nonlinearities which can be constructed to vanish at the origin under certain conditions. This property allows the concept of eigenvalue extension of linear time-varying systems to be applied in the interpretation of the results. An example problem, motivated by a comet sample return mission prototype, is given to demonstrate the sensitivity of the disturbance rejection capacity to maneuver time. The results reinforce the notion that large-angle spacecraft reorientation should place a premium on finesse (i.e., smooth, bounded motion), rather than speed (i.e., minimum time control).

[View Full Paper]

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AAS 13-097

PAYLOAD USE, CLOSE PROXIMITY OPERATIONS AND GUIDANCE, NAVIGATION AND CONTROL AT NEAR EARTH ASTEROIDS

Julie Bellerose,* Piero Miotto,† Leena Singh,‡ Anthony Colaprete,§ Daniel Andrews** and Steve Warwick††

Mission operations at small bodies depend mostly on targets' size, and the mission objectives. The NEA User Team (NUT) defined a set of requirements that a robotic precursor should satisfy prior to sending a crew to a near-Earth asteroid. We give a quick review of instruments that can be used at NEAs to obtain the required data, and discuss associated proximity and surface operations. Finally, we discuss a case study, the NEA Close Rendezvous and Operations Satellite (NCROSS), which is a LCROSS derived low-cost concept that tackles the additional challenge of autonomously approaching and intercepting a small, tumbling asteroid with an unknown variety of weathered surface features, orientations and illuminations. NCROSS enables a variety of future robotic and human missions to safely approach, survey, touch or deflect unpredictable and uncooperative targets. [View Full Paper]

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RENDEZVOUS, PROXIMITY OPERATIONS AND DOCKING

SESSION X

Increasingly autonomous capability in rendezvous, proximity operations, and docking (RPOD) of space assets will be required for future robotic and human exploration missions. Applications range broadly, including in-space assembly and disassembly, satellite servicing, robotic inspection, proximity operations about Primitive Bodies and Near Earth Objects, and planetary sample return. RPOD is a system capability enhanced by innovative system-level as well as component-level technology advancements. This session explores current and future applications, state of the art and advancement of related technologies for RPOD.

National Chairpersons:	MiMi Aung Jet Propulsion Laboratory
	Brook Sullivan, DARPA
Local Chairpersons:	Tim Bevacqua Lockheed Martin Space Systems
	Joel Nelson Ball Aerospace & Technologies Corp.

The following paper was not available for publication:

AAS 13-106
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 13-107 to -110

AAS 13-101

GYRO-AIDED VISION-BASED RELATIVE POSE ESTIMATION FOR AUTONOMOUS RENDEZVOUS AND DOCKING

Vaibhav Ghadiok,* Jeremy Goldin† and David Geller‡

As the number of orbiting satellites grows, coupled with the desire to utilize existing satellites for even longer periods, the needs to refuel, repair, re-orbit or de-orbit satellites, and remove debris have become increasingly important. Close proximity, or rendezvous, operations require accurate relative pose estimation. In this work, the 6-degrees of freedom (DOF) pose and 3-D model of a resident space object SOO) are estimated using imagery from a monocular camera, based on Structure from Motion (SfM) techniques. Natural features on the SO are extracted and tracked over time to give an estimate of the relative pose between the host platform and the SO, with a 3-D model of the SO estimated simultaneously and further refined using Bundle Adjustment. This paper additionally examines the option of obtaining more accurate relative attitude estimation by fusing the pose estimates provided by the camera with the angular velocity measurements provided by the gyroscopes on the host platform. But for small satellites, there are restrictions of using only low-cost, low-quality sensors such as MEMS-based gyroscopes that are highly susceptible to noise, for which we propose the use of a nonlinear complementary filter for attitude estimation by fusing estimates from the monocular camera and MEMS-based gyroscopes to obtain accurate estimation of the roll, pitch and yaw of the host platform. Attitude estimation using the pose from the camera and the gyroscopes is validated on a testbed consisting of a full-scale model of a small satellite (acting as a SO) and experimental results demonstrating the efficacy of the outlined approach for close proximity operations are presented. [View Full Paper]

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ADVANCED 3D SENSING ALGORITHMS AND COMPUTER ARCHITECTURES FOR SIMULTANEOUS MAPPING AND CLOSE PROXIMITY OPERATIONS

Manoranjan Majji* **and John L. Junkins†**

Sensing algorithms and computational architectures play an important role in the simultaneous location, mapping and close proximity operations of spacecraft. Along with an error characterization of the relative motion states, a sensor fusion method is proposed in this paper that utilizes a double bootstrapping approach to perform real time computation of measurement error statistics. A generalized QUEST model is discussed that includes the translation vector in the close proximity navigation measurements. Based on the generalized QUEST measurement model, a multiplicative extended Kalman filter is proposed to estimate the relative motion states between the vehicles of interest. It is shown that this technique can be used to estimate the full attitude and relative motion translation states even at modest sampling rates. A sensitivity analysis is performed to identify the observable state estimation error accuracies. [View Full Paper]

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AAS 13-103

HARDWARE IN THE LOOP VALIDATION OF GNC FOR RVD/RVC SCENARIOS

Pablo Colmenarejo,[*] Valentín Barrena[†] and Thomas Voirin[‡]

The big challenge of new technologies, particularly related to GNC systems, is to achieve a TRL (Technology Readiness Level) high enough before flying in order to minimize the failure risks. Most of GNC related technologies need, in fact, to fly as experiment before being declared as validated for space use as mission baseline. In flight experiment opportunities are, nevertheless, expensive and very limited in terms of number of opportunities. This is especially true for new mission concepts in Europe such as Formation Flying or Rendezvous and Docking/capture.

ESA HARVD activity (High integrity Autonomous RendezVous and Docking control system for MSR Capture scenario and Earth servicing missions), has been developed by an industrial team led by GMV, and includes a design and validation strategy that, using an incremental validation approach concept, starts by Model In the Loop (MIL, based on Matlab/Simulink), passes through SW In the Loop (SIL, non real-time), arrives to Processor In the Loop (PIL, real-time) and finalizes with Hardware in the Loop (HIL) with camera and Lidar HW breadboards in the loop with air-to-air signal transmission and space-representative relative motion generated by specific robotic devices synchronized with the GNC real-time host system and processor. Representative illumination conditions are guaranteed by the use of Fresnel lights.

This paper describes briefly the above-mentioned Design, Development, Verification and Validation (DDVV) approach and focuses mainly on the integration of the PIL real-time test bench with the specific dynamic test bench devices (called ***platform®*** and including two robotic arms, one of them hosted on a linear axis with motion capability up to 15 meters), the performance of the tests (several scenarios including the use of scaled mock-ups of MSR mission Sample Canister, the MSR Mars Ascent Vehicle and the IBDM Demo mission target spacecraft including a model – geometry representative – of the IBDM docking mechanism) and the obtained dynamic tests results (including a video of some of the cases) and lessons learnt. In addition, comparison of HIL test results with PIL/SIL/MIL results serve to validate the PIL/SIL/MIL test benches/simulator environment, to demonstrate the coherency of the DDVV approach and its use for later (and faster) design iterations (if needed). [View Full Paper]

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AAS 13-104

POSE DETERMINATION USING ONLY 3D RANGE IMAGES FROM THE STORRM MISSION

Reuben R. Rohrschneider* and William Tandy†

NASA's future plans for space vehicles call for the ability to Autonomously Rendezvous and Dock (AR&D) with the International Space Station (ISS) and other targets. This requires sensors and algorithms capable of determining the relative position and orientation (pose) between the target and chase vehicles under the drastically varying lighting conditions of low Earth orbit and beyond.

To this end, Ball Aerospace has developed algorithms to produce six degree-of-freedom navigation data from 3D point clouds. The algorithms require a-priori knowledge of the target vehicle geometry and a range image of the target vehicle for in-flight pose determination (no visible or reflective targets are needed). The algorithms have previously been tested in simulations with good results. With flight data from the STORRM mission now available, the algorithms have been run on the data series produced during the first docking maneuver of the Space Shuttle on flight day 3. Comparison of our results to the Best Estimated Trajectory (BET) produced by the Draper Laboratory indicate good agreement for the 3 translational degrees of freedom and rotation about the line of sight. This application is beyond the scope of the original STORRM mission, and improvements to the sensor are identified for future use on future non-cooperative missions. Computing accurate rotations about the other two axes has proven more difficult. A more thorough calibration is the primary recommendation for future sensor builds, and is an easily remedied problem that will enable AR&D with semi-cooperative bodies for future spacecraft servicing and active orbital debris removal missions. [View Full Paper]

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RENDEZVOUS, PROXIMITY OPERATIONS AND DOCKING/MATING TECHNOLOGIES FOR ON-ORBIT SERVICING[*]

Andrew Allen,[†] John Lymer,[‡] Cameron Ower,[§]
Dan King[**] and Christopher Langley[††]

Rendezvous, Proximity Operations, and Docking/Mating (RPOD) have often been viewed as difficult or risky and hence are sometimes avoided by space infrastructure planners and architects. Contrary to this belief, significant progress has been made in RPOD in ground-based research and new capabilities development, in-space flight demonstrations, and for ongoing operational use. Some of the key technologies being progressed include rendezvous and proximity operations sensors and cameras, vision-based relative navigation algorithms, remote operations and telepresence, as well as docking and capture/berthing systems.

MDA has been a key contributor to such RPOD developments for both cooperative/pre-planned and non-cooperative/unprepared robotic operations, addressing both government and commercial mission applications. Examples of MDA's involvement include XSS-11, Orbital Express (OE), Space Infrastructure Services (SIS), Next Generation Canadarm (NGC), International Berthing/ Docking Mechanism (IBDM), International Space Station (ISS) Visiting Vehicles, and most recently, DARPA Phoenix.

This paper will describe some of MDA's contributions to recent and ongoing RPOD work, with particular emphasis on which technological aspects should be considered low risk versus areas that may require further development and maturation. The paper will also outline how these RPOD capabilities could positively impact robust new space infrastructures with the key objective of lowering both the initial development and deployment costs and the overall lifecycle operating costs. [View Full Paper]

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NESTED CONTROL LOOPS LEVERAGING PAYLOAD CAPABILITIES

SESSION XI

Traditional spacecraft attitude control systems may at times be supplemented by high-precision capabilities inherent in their payloads. The use of scan mirrors, steering mirrors, narrow-field focal planes, or other features built-in to the payload instruments may be used to provide much higher pointing precision and/or agility than can be done cost-effectively at the vehicle level. This session explores the issues encountered and capabilities afforded by these types of nested control systems in past, present, and future missions.

National Chairpersons:

Paul Brugarolas
Jet Propulsion Laboratory

Doug Freesland
ACS Engineering

Local Chairpersons:

Jim Chapel
Lockheed Martin Space Systems

Bill Frazier
Ball Aerospace & Technologies Corp.

The following papers were not available for publication:

AAS 13-111
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AAS 13-118
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 13-119 to -120

ORBIT AND ATTITUDE CONTROL FOR GRAVIMETRY DRAG-FREE SATELLITES

Enrico Canuto,[*] Andrés Molano JImenez[†] and Marcello Buonocore[‡]

The paper outlines orbit and attitude control problems of a long-distance (>100 km) two-satellite formation for the Earth gravity monitoring. Modeling and control design are done within the Embedded Model Control framework. They show how disturbance dynamics and rejection are mandatory to solve control problems. Orbit and attitude control can be treated separately except for the thrust dispatching law (not treated here) in charge of an all-propulsion actuation. Orbit and attitude control split into sub-problems to be designed in a hierarchical way. The inner loop is a wide-band drag-free control aiming to zero the linear non gravitational accelerations in the orbit control and the total angular acceleration in the attitude case. Drag-free demands for disturbance measurement and rejection by means of a specific disturbance dynamics and state predictor. The orbit outer loops are altitude and distance control that are designed to meet formation requirements. The attitude outer loop is in charge of rejecting the residual drag-free bias and drift, which demands a narrow-band control which is suitable for star tracker measurements, and the alignment of the optical axes of each satellite to the satellite-to-satellite line, which demands accurate sensors and a wider bandwidth. Simulated and experimental results are provided. [View Full Paper]

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GOES-R ADVANCED BASELINE IMAGER PRECISE POINTING CONTROL AND IMAGE COLLECTION

David A. Igli*

The Geostationary Operational Environment Satellites (GOES) program has a history of precise instrument pointing and registration of imagery collected from geosynchronous altitude. Precision pointing for the heritage GOES program has come at a price of ground processing and high order estimates of line of sight motion which are used to update pointing commands. In the next generation GOES-R concept with the Advanced Baseline Imager (ABI), the spacecraft communicates with the instrument to allow real time line of sight compensation for precise pointing. This streamlines ground operations and simplifies the ground to spacecraft/instrument command interface. While the GOES-R spacecraft navigation and control requirements are stringent, it is not practical to control the spacecraft to point to the required accuracy for the ABI instrument. Therefore, the instrument must compensate for the spacecraft dynamics, attitude and orbit control offsets to achieve the precise pointing accuracy required to accomplish the GOES-R mission. This paper discusses the GOES-R mission pointing, ABI control architecture and integration with the spacecraft to achieve the necessary precision while reducing ground command and control operations. [View Full Paper]

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AAS 13-114

FREQUENCY MEASUREMENT OF SPACECRAFT POINTING USING THE HIRISE CAMERA

Alan Delamere,[*] Jim Bergstrom,[†] Jim Chapel,[‡] Audrie Fennema,[§] Randolph Kirk,[**] Alfred McEwen[§] and Sarah Mattson[§]

The Mars Reconnaissance Orbiter (MRO) carries a unique instrument capable of determinating small spacecraft disturbances in the micro-radian range. The High Resolution Imaging Science Experiment (HiRISE) camera has been returning quality images since MRO entered its primary Science phase in November 2006. HiRISE data demonstrates that spacecraft motions are smaller than required in high stability mode, so even higher-resolution imaging would not be limited by pointing jitter. Lower-frequency disturbances introduce geometric distortions, but the overlapping HiRISE detectors enable measuring and removing this jitter. [View Full Paper]

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AAS 13-115

TRADING ACTIVE PAYLOAD POINTING WITH SPACECRAFT BUS AGILITY

Tim Hindle,* M. Brett McMickell* and Brian Hamilton*

Active payload pointing has been discussed in the past as a method to maintain high pointing accuracy and to control vibrations. Much of this work has focused on the application of the active pointing system alone. This paper describes the trades between active payload pointing and the agility of the spacecraft bus. Based on the objectives of the mission, an overall control strategy combining active payload pointing with the attitude control system can be implemented, where there are tradeoffs between target collection capability, jitter performance, payload pointing system requirements, and momentum control system requirements. [View Full Paper]

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AAS 13-116

THE OpTIIX POINTING CONTROL SYSTEM

P. Brugarolas, J. Alexander, D. Bayard, D. Boussalis, M. Boyles, E. Litty, R. Goullioud, S. Mohan, S. Ploen, M. Wette and Z. Rahman*

K. Ess and D. Magruder†

The Optical Testbed and Integration on ISS eXperiment (OpTIIX) is a modularized, actively controlled, robotically assembled, scalable, segmented telescope architecture to be demonstrated on the International Space Station (ISS). This paper describes the OpTIIX Pointing Control System (PCS). The PCS has three pointing stages: a 3-axis gimbal that points the entire telescope, and two steering mirrors within the telescope (a coarse steering mirror at a pupil and a fine steering tertiary). The gimbal stage is controlled using the telescope attitude estimates derived from a Star Tracker and Inertial Measurement Unit (IMU) mounted on the telescope base. The coarse steering mirror compensates for the residual gimbal attitude errors as sensed by the star tracker and gyro. The fine steering tertiary is in a high frequency line-of-sight stabilization loop that uses a fine guidance sensor within the telescope instrument. [View Full Paper]

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AAS 13-117

STRATOSPHERIC BALLOON-BORNE TELESCOPE MODELING AND PRECISION-POINTING

J. Aldrich,* P. Brugarolas,* J. Lanzi,†
D. Stuchlik,† W. Traub* and S. Unwin*

A major hurdle in reducing the perceived risk of flying balloon-borne precision-pointing telescope missions has been in validating the imposition of the gondola dynamics on the accuracy with which an instrument can be kept pointed at a celestial target. For purposes of mitigating this risk, this paper introduces a closed-loop dynamic modeling framework that is relevant for precision-pointing control of sub-orbital balloon-borne telescopes. The model is designed to support a multi-stage pointing architecture comprising: a balloon-mounted cable-suspended gondola, a course azimuth control system, a multi-axis nested gimbal frame structure with sub-arcsec stability, and a fine-guidance stage consisting of both a telescope-mounted angular rate sensor and guide CCDs in the focal plane to drive a Fast-Steering Mirror. Although a general nonlinear dynamic simulation model is assumed, our chosen parameterization exploits the fact the geometry of the flight train is nominally aligned with gravity, thereby facilitating the model linearization step. Nonlinear simulation trades are also included for purposes of capturing the nonlinear components of the control hardware as well as the pathological effects due to bearing rumble, mass-imbalances, and frozen-cable effects. We discuss the results of these pointing simulation tests in terms of the system-level design constraints that would support a mission to characterize exoplanet systems by direct imaging. [View Full Paper]

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RECENT EXPERIENCES IN GUIDANCE AND CONTROL

SESSION XII

Lessons learned through experience prove most valuable when shared with others in the GN&C community. This session, which is a traditional part of the conference, provides a forum for candid sharing of insights gained through successes and failures. Past conferences have shown this session to be most interesting and informative.

Local Chairperson: James McQuerry
Ball Aerospace & Technologies Corp.

The following papers were not available for publication:

AAS 13-123
(Paper Withdrawn)
AAS 13-127
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 13-128 to -130

AAS 13-121

FORMATION FLIGHT ATTITUDE CONTROL APPROACH AND OPERATIONS RESULTS OF THE NASA GRAIL SPACECRAFT*

Christine Edwards-Stewart, Dave Eckart, Ryan Olds and Thomas Kennedy†

The Gravity Recovery and Interior Laboratory (GRAIL) mission is composed of twin spacecraft tasked with precisely mapping the gravitational field of the moon. GRAIL science collection requires that the two spacecraft operate in the same orbit plane and with precise relative separation and pointing, which evolved through the primary and extended mission Science phases. Extended mission operations involved flying the formation much closer to the surface of the Moon than required by the primary mission. This introduced several challenges to attitude planning complicated by the orbit maintenance activities being performed on each spacecraft. A description of the formation flight and attitude control approach that was implemented on the GRAIL spacecraft will be accompanied by a presentation of simulation and flight results and discussion of some of the challenges encountered in operations. [View Full Paper]

† GRAIL Attitude Control Subsystem Team, Lockheed Martin Space Systems Company.

ATTITUDE CONTROL AND ESTIMATION ACTIVITIES DURING COMMISSIONING OF THE TWIN VAN ALLEN PROBES SPACECRAFT

M. N. Kirk,* G. D. Rogers,* A. M. Fosbury,*
J. H. Wirzburger* and R. M. Vaughan*

The Van Allen Probes were launched into Earth orbit on August 30, 2012 for a nominal two-year mission to study the Earth's radiation belts and their interaction with the Sun. The two spin-stabilized spacecraft have onboard Guidance and Control hardware consisting of Sun sensors, passive nutation dampers, and eight mono-propellant hydrazine thrusters. Magnetometer data are provided by a science instrument. Attitude estimates and open-loop maneuver designs are generated on the ground. During the first 60 days of commissioning the Guidance and Control team designed and executed a total of 24 maneuvers, performed calibrations of the Sun sensors, thrusters, and magnetometers, computed changes in spacecraft moments of inertia through various spacecraft solar array panel and instrument boom deployments, and better characterized the dynamical behavior of the twin spacecraft in their highly elliptical orbits. This paper describes the Van Allen Probes spacecraft, the attitude estimation and control activities conducted during the first 60 days of commissioning, and the performance of the spacecraft and ground software throughout this period of time. [View Full Paper]

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AAS 13-124

CLOUDSAT RECOVERY TO SCIENCE OPERATIONS FOLLOWING A BATTERY ANOMALY

Ian J. Gravseth*

Between April 17th – 18th 2011 CloudSat experienced multiple under-voltage (UV) faults which activated the emergency mode controller (EMC), leaving the vehicle in a power positive but completely passive spin, halting normal operations. Subsequent attempts to perform the standard recovery procedure were unsuccessful – the battery was unable to support the spacecraft loads through eclipse even in its lowest power mode. Subsequent investigation revealed that CloudSat's effective battery's capacity had dropped from nearly 50 Amp-hours before launch to approximately 2.5 Amp-hours. Given CloudSat's lengthy eclipses and the spacecraft's power requirements, it was apparent that CloudSat was incapable of supporting the science payload and most subsystem loads through eclipse. To save the mission a new method of controlling and operating the vehicle would have to be developed in which the vehicle is only actively controlled for approximately 2/3rds of each orbit. In addition, the battery's limitations also required the solar arrays to face the sun prior to powering on any components. This paper discusses the recovery of the spacecraft and the new methods of controlling the vehicle which the CloudSat team has developed to return the vehicle to an operational state. [View Full Paper]

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AAS 13-125

ODYSSEY PREPARATIONS FOR AND ROLE IN CURIOSITY ENTRY DESCENT AND LANDING WITH FOCUS ON ATTITUDE SELECTION

Noel H. Hughes and John Balke*

The Odyssey Mars Orbiter provided real time bent pipe data relay of data to Earth from the Mars Science Laboratory, Curiosity, during the Entry, Descent and Landing (EDL) phase of the mission. In this paper we will describe the motivation for having real time and non-real time relay communication from Curiosity during EDL and the requirements and objectives applicable to Odyssey to effect such communication. Next we describe the Odyssey vehicle and mission and outline the events and actions by the Odyssey team leading up to Curiosity EDL, including the loss of a reaction wheel which led to two safe mode entries and subsequent recovery efforts. In the remainder of the presentation we will describe how requirements, imposed both by Curiosity EDL and by Odyssey health and safety and communication restrictions, drove the attitude profile of Odyssey during EDL and the process by which this attitude profile was developed. [View Full Paper]

* Lockheed Martin Space Systems Company.

AAS 13-126

IN-ORBIT RESULTS OF TELECOM SATELLITES PROPULSION MONITORING

Jerome Maureau,[*] Christine Fallet[*] and Paola Van Troostenberghe[†]

TELECOM-2 geostationary satellites have been de-orbited and de-activated at the end of their operational life. As they were designed prior to the IADC guidelines or French space law, satellites were neither compliant nor submitted to these regulations. Although, de-orbiting operations were led such that later requirements are fulfilled at the utmost. During tanks passivation, attitude control was a main concern, as transition from bi-propellant to mono-propellant thrust induces a loss of 80% to 90% of the nominal force. To insure the success of the end-of-life operations, thruster forces were monitored from the ground, to identify potential risks and tune passivation parameters accordingly. The paper will present the method and the on-orbit results through TELECOM-2C and TELECOM-2D cases. [View Full Paper]

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POSTER SESSION

SESSION 0

Local Chairpersons: Michael Osborne
Lockheed Martin Space Systems

The following papers were not available for publication:

AAS 13-002
(Paper Withdrawn)
AAS 13-003
(Paper Withdrawn)

The following paper numbers were not assigned:

AAS 13-007 to -010

DYNAMICS MODELING OF ELECTROMAGNETIC FORMATION FLIGHT

Andrew R. Hilton,* Gregory J. Eslinger† and David W. Miller‡

Electromagnetic formation flight (EMFF) is a method of holding satellite arrays in a formation without the use of propellant. A formation of smaller satellites that work together can be more effective and cheaper than one larger satellite performing a similar mission. EMFF will enable the United States Air Force to develop flexible, robust space systems by splitting different systems and payloads into modules that link together on orbit and fly in a formation. Such systems will reduce the complexity of design as well as increase the ability to respond to unforeseen occurrences during mission operations. The concept of EMFF relies on the fact that the spacecraft in the formation are flying relative to each other and uses attraction and repulsion forces to actuate the system. The research presented here analyzes these relative forces while detailing the development and verification of a Simulink dynamics model for an electromagnetic formation flight project at the Space Systems Laboratory. Biot- Savart's law is used to characterize the magnetic fields from each coil and model the resulting forces and torques. The model uses finite element analysis to compute the forces and torques exchanged between different segments on the two coils. The simulation has been accurate in modeling the forces and torques induced by resonant coils as a result of their relative position and orientation thereby allowing future researchers to develop and test formation-flying control algorithms before using the valuable on-orbit time allocated for hardware testing. [View Full Paper]

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AAS 13-004

MODEL-BASED DESIGN FOR LARGE HIGH-INTEGRITY SYSTEMS: A DISCUSSION ON LOGIC-INTENSIVE ALGORITHMS*

Mike Anthony,† William B. Campbell‡ and Becky Petteys§

A large portion of the embedded software found in today's vehicles, be they sea-based, land-based, aircraft, or spacecraft, falls into the category of logic-intensive algorithms. The use of state machines has long been a common modeling practice for logic-intensive algorithms. As an abstraction of decision making procedures, finite state machines have always been an important construct in software engineering. Furthermore, it is hypothesized that the use of state machines with constrained semantics and deterministic behavior is critical for the development and verification of high-integrity applications.

This hypothesis is examined by comparing several different Model-Based Design approaches for the development of logic-intensive algorithms in a high-integrity environment. The goal is to understand the tradeoffs of several different modeling approaches at each step of a high-integrity workflow. The modeling approaches examined are: MATLAB®, Simulink®, Stateflow® using a subset of Classic semantics, Stateflow using Mealy[1] semantics, and Stateflow using Moore[2] semantics. These modeling approaches are compared at each step of a sample high-integrity software development workflow. This provides an opportunity to comprehensively evaluate the merits of each approach for development, automatic code generation, and model and code verification and validation.

The evaluation concludes that each approach is valid and provides significant benefit in at least one step of the workflow. As such, it is important that the goals and process requirements for a project be well understood before making a decision on which approach is optimal. However, within the context of the sample high-integrity workflow discussed in this paper, the use of Stateflow using Classic, Mealy, or Moore semantics can achieve optimal results. [View Full Paper]

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GRAVMOD-2: A NEW TOOL FOR PRECISE GRAVITATIONAL MODELING OF PLANETARY MOONS AND SMALL BODIES

Valentino Zuccarelli,* Sven Weikert,† Raul Cadenas‡ and Irene Huertas§

This paper describes the ESA gravity modeling tool GRAVMOD2, its main functionalities, on-board GNC propagator, on-going studies and expected evolutions. GRAVMOD2 is the follow-up and extension activity of the GRAVMOD1 tool. It is a software tool developed by Astos Solution and GMV for the European Space Agenda, which adds guidance analysis and on-board manoeuvers capabilities to the gravitational modeling core of GRAVMOD1. The unique mathematical models and architecture make it particularly suitable for the modeling of the gravity field of highly irregular bodies such as asteroids or comets. [View Full Paper]

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ORION EXPLORATION FLIGHT TEST-1 CONTINGENCY DROGUE DEPLOY VELOCITY TRIGGER

Robert S. Gay,[*] Susan Stachowiak[†] and Kelly Smith[‡]

As a backup to the GPS-aided Kalman filter and the Barometric altimeter, an “adjusted” velocity trigger is used during entry to trigger the chain of events that leads to drogue chute deploy for the Orion Multi-Purpose Crew Vehicle (MPCV) Exploration Flight Test-1 (EFT-1). Even though this scenario is multiple failures deep, the Orion Guidance, Navigation, and Control (GN&C) software makes use of a clever technique that was taken from the Mars Science Laboratory (MSL) program, which recently successfully landing the Curiosity rover on Mars. MSL used this technique to jettison the heat shield at the proper time during descent. Originally, Orion use the un-adjusted navigated velocity, but the removal of the Star Tracker to save costs for EFT-1, increased attitude errors which increased inertial propagation errors to the point where the un-adjusted velocity caused altitude dispersions at drogue deploy to be too large. Thus, to reduce dispersions, the velocity vector is projected onto a “reference” vector that represents the nominal “truth” vector at the desired point in the trajectory. Because the navigation errors are largely perpendicular to the truth vector, this projection significantly reduces dispersions in the velocity magnitude. This paper will detail the evolution of this trigger method for the Orion project and cover the various methods tested to determine the reference “truth” vector; and at what point in the trajectory it should be computed. [View Full Paper]

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