GUIDANCE, NAVIGATION, AND CONTROL 2019

Front Cover Illustration:

"NASA's Kepler space telescope may be retired, but the discoveries continue to rack up for this historic planet-hunting mission. Kepler rang in the new year with several new planet discoveries, including a previously overlooked planet of an unusual size, as well as a super Earth and a Saturn-sized world orbiting a Sun-like star.

In the meantime, the Kepler mission has released its final record of the spacecraft's full field of view before the depletion of fuel permanently ended its work. NASA retired the spacecraft on Oct. 30, 2018, to a safe orbit.

The "last light" image taken on Sept. 25 represents the final page of the final chapter of Kepler's remarkable journey of data collection. It bookends the moment of intense excitement nine and a half years earlier when the spacecraft first opened its eye to the skies and captured its "first light" image. Kepler went on to discover more than 2,600 worlds beyond our solar system and statistically proved that our galaxy has even more planets than stars.

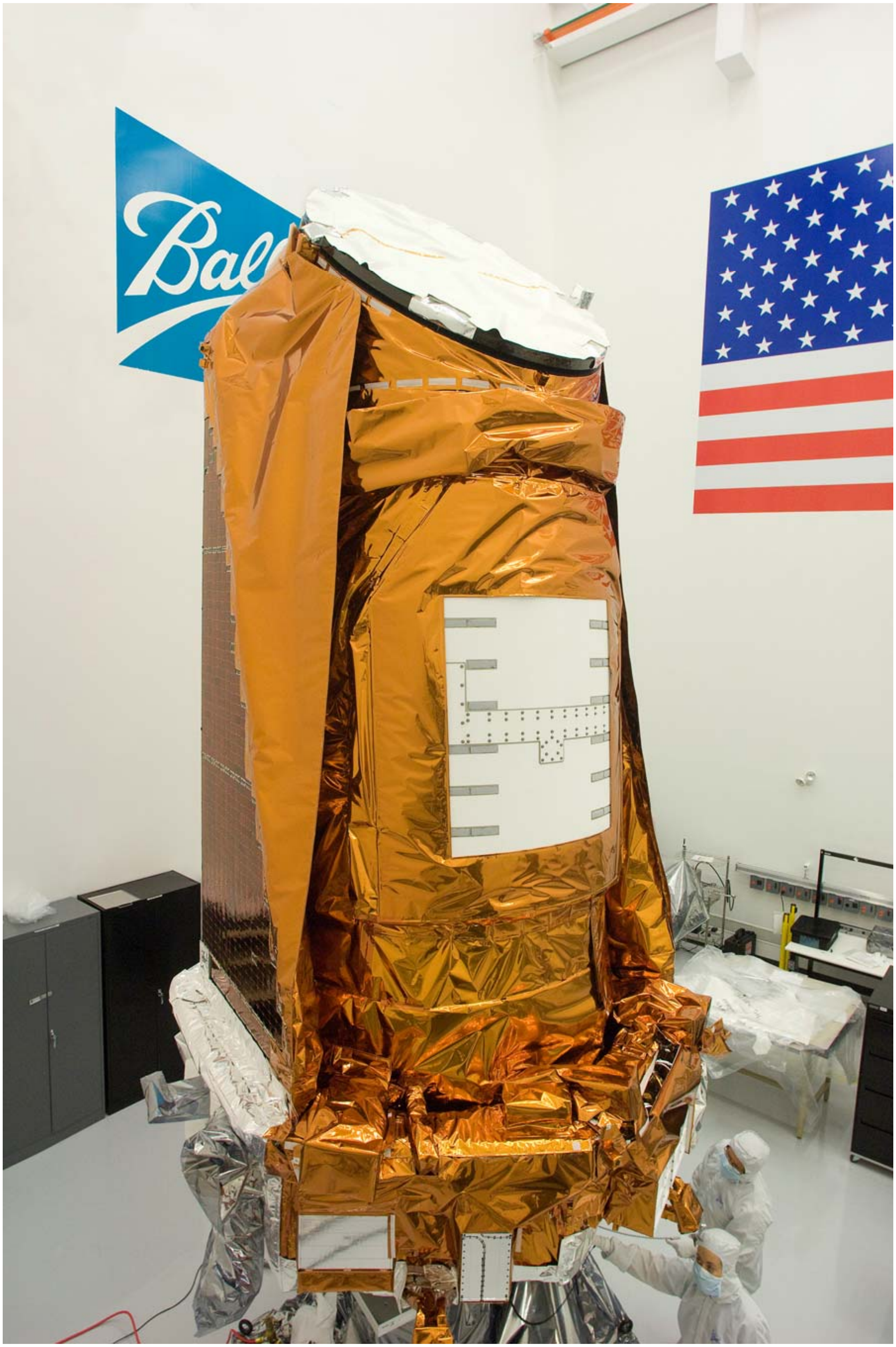
The blackened gaps in the center and along the top of the image are the result of earlier random part failures in the camera. Due to the modular design, the losses did not impact the rest of the instrument.

For this final field of view, Kepler's last observation campaign in its extended mission, the telescope was pointed in the direction of the constellation Aquarius. It caught a glimpse of the renowned TRAPPIST-1 system with its seven rocky planets, at least three of them believed to be temperate worlds. Another target was the GJ 9827 system, a nearby bright star that hosts a planet that is considered an excellent opportunity for follow up observations with other telescopes to study an atmosphere of a faraway world."

Reference Link:
https://www.nasa.gov/image-feature/ames/kepler-s-final-image-shows-a-galaxy-full-of-possibilities

Frontispiece Illustration:

Kepler sits in the cleanroom at Ball Aerospace. Kepler was launched in March 2009 into an Earth-trailing heliocentric orbit. After two reaction wheel failures, first in July 2012 and then in August 2013, Kepler entered its K2 extended mission. Innovative control implemented by managing solar pressure and the judicious use of thrusters allowed Kepler to continue observing in 80-day campaigns with only two reaction wheels. Last light for the space telescope was on September 25, 2018 due to fuel depletion. Despite the mission ending, it is expected that the voluminous Kepler data will allow for even more discoveries in the years to come. (Image courtesy of Ball Aerospace).



American Astronautical Society

GUIDANCE, NAVIGATION, AND CONTROL 2019

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Edited by
Heidi E. Hallowell

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FOREWORD

HISTORICAL SUMMARY

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

In the late seventies, Bud Gates, Don Parsons and Sherm Seltzer jointly came up with the idea of convening a broad spectrum of experts in the field for a fertile exchange of aerospace control ideas. At about this same time, Dan DeBra and Lou Herman had discussed a similar plan.

Bud and Don approached the AAS Section Chair, Bob Culp, with their proposal. In 1977, Bud Gates, Don Parsons, and Bob Culp organized the first conference, and began the annual series of meetings the following winter. Dan and Lou were delighted to see their concept brought to reality and joined enthusiastically from afar. In March 1978, the First Annual Rocky Mountain Guidance and Control Conference met at Keystone, Colorado. It met there for eighteen years, moving to Breckenridge in 1996 where it has been for more than 20 years. The 2018 Conference was the 41th Annual AAS Rocky Mountain Guidance, Navigation and Control Conference.

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

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

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

A tradition from the beginning and retained until 2014 had been the Conference banquet. A general interest speaker was a popular feature. The banquet speakers included:

Banquet Speakers

1978 Sherm Seltzer, NASA MSFC, told a joke
1979 Sherm Seltzer, Control Dynamics, told another joke
1980 Andrew J. Stofan, NASA Headquarters, “Recent Discoveries through Planetary Exploration.”
1981 Jerry Waldvogel, Cornell University, “Mysteries of Animal Navigation.”
1982 Robert Crippen, NASA Astronaut, “Flying the Space Shuttle.”
1983 James E. Oberg, author, “Sleuthing the Soviet Space Program.”
1984 W. J. Boyne, Smithsonian Aerospace Museum, “Preservation of American Aerospace Heritage: A Status on the National Aerospace Museum.”
1985 James B. Irwin, NASA Astronaut (retired), “In Search of Noah’s Ark.”

1986 Roy Garstang, University of Colorado, “Halley’s Comet.”
1987 Kathryn Sullivan, NASA Astronaut, “Pioneering the Space Frontier.”
1988 William E. Kelley and Dan Koblosh, Northrop Aircraft Division, “The Second Best Job in the World, the Filming of Top Gun.”
1989 Brig. Gen. Robert Stewart, U.S. Army Strategic Defense Command, “Exploration in Space: A Soldier-Astronaut’s Perspective.”
1990 Robert Truax, Truax Engineering, “The Good Old Days of Rocketry.”
1991 Rear Admiral Thomas Betterton, Space and Naval Warfare Systems Command, “Space Technology: Respond to the Future Maritime Environment.”
1992 Jerry Waldvogel, Clemson University, “On Getting There from Here: A Survey of Animal Orientation and Homing.”
1993 Nicholas Johnson, Kaman Sciences, “The Soviet Manned Lunar Program.”
1994 Steve Saunders, JPL, “Venus: Land of Wind and Fire.”
1995 Jeffrey Hoffman, NASA Astronaut, “How We Fixed the Hubble Space Telescope.”
1996 William J. O’Neil, Galileo Project Manager, JPL, “PROJECT GALILEO: JUPITER AT LAST! Amazing Journey—Triumphant Arrival.”
1997 Robert Legato, Digital Domain, “Animation of Apollo 13.”
1998 Jeffrey Harris, Space Imaging, “Information: The Defining Element for Superpowers-Companies & Governments.”
1999 Robert Mitchell, Jet Propulsion Laboratories, “Mission to Saturn.”
2000 Dr. Richard Zurek, JPL, “Exploring the Climate of Mars: Mars Polar Lander in the Land of the Midnight Sun.”
2001 Dr. Donald C. Fraser, Photonics Center, Boston University, “The Future of Light.”
2002 Bradford W. Parkinson, Stanford University, “GPS: National Dependence and the Robustness Imperative.”
2003 Bill Gregory, Honeywell Corporation, “Mission STS-67, Guidance and Control from an Astronaut’s Point of View.”
2004 Richard Battin, MIT, “Some Funny Things Happened on the Way to the Moon.”
2005 Dr. Matt Golombeck, Senior Scientist, MER Program, JPL, “Mars Science Results from the MER Rovers.”
2006 Mary E. Kicza, Deputy Assistant Administrator for Satellite and Information Services, NASA, “NOAA: Observing the Earth from Top to Bottom.”
2007 Patrick Moore, Consulting Senior Life Scientist, SAIC and the Navy Marine Mammal Program, “Echolocating Dolphins in the U.S. Navy Marine Mammal Program.”
2008 Dr. Ed Hoffman, Director, NASA Academy of Program and Project Leadership, “The Next 50 Years at NASA – Achieving Excellence.”
2009 William Pomerantz, Senior Director for Space, The X Prize Foundation, “The Lunar X Prize.”
2010 Berrien Moore, Executive Director, Climate Central, “Climate Change and Earth.”
2011 Joe Tanner, Former Astronaut; Senior Instructor, University of Colorado, “Building Large Objects in Space.”
2012 Greg Chamitoff, Ph.D., NASA Astronaut, “Completing Construction of the International Space Station — The Last Mission of Space Shuttle Endeavour.”
2013 Thomas J. “Dr. Colorado” Noel, Ph.D., Professor of History and Director of Public History, Preservation & Colorado Studies at University of Colorado Denver, “Welcome to the Highest State: A Quick History of Colorado.”

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

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

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." In 2015 and 2017 the Orion capsule development resulted in special sessions on the GN&C aspects of capsule design. In 2017 the extensive list of technology demonstration missions performed in Europe inspired a session on "European

Technology Demonstrations." In 2019, high interest in new navigation technologies and methods for ground-based, GNSS-based, and onboard spacecraft sensor navigation applications resulted in two very interesting and relevant sessions.

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

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

Scholarship Winners

	Aerospace Engineering Sciences	**Electrical and Computer Engineering**
1981	Jim Chapel	
1982	Eric Seale	
1983	Doug Stoner,	John Mallon
1984	Mike Baldwin,	Paul Dassow
1985	Bruce Haines,	Steve Piche
1986	Beth Swickard,	Mike Clark
1987	Tony Cetuk,	Fred Ziel
1988	Mike Mundt,	Brian Olson
1989	Keith Wilkins,	Jon Lutz
1990	Robert Taylor,	Greg Reinacker
1991	Jeff Goss,	Mark Ortega
1992	Mike Goodner,	Dan Smathers
1993	Mark Baski,	George Letey
1994	Chris Jensen,	Curt Musfeldt
1995	Mike Jones,	Curt Musfeldt
1996	Karrin Borchard,	Kirk Hermann
1997	Tim Rood,	Ui Han
1998	Erica Lieb,	Kris Reed
1999	Trent Yang,	Adam Greengard
2000	Josh Wells,	Catherine Allen
2001	Justin Mages,	Ryan Avery
2002	Tara Klima,	Kiran Murthy
2003	Stephen Russell,	Andrew White
2004	Trannon Mosher,	Negar Ehsan
2005	Matt Edwards,	Henry Romero
2006	Arseny Dolgove,	Henry Romero
2007	Kirk Nichols,	Chris Aiken
2008	Nicholas Hoffmann,	Gregory Stahl
2009	Filip Maksimovic,	Justin Clark
2010	John Jakes,	Filip Maksimovic
2011	Weceslao Shaw-Cortez Jr.,	Andrew Tomas
2012	Jacob Hynes,	Nicholas Mati
2013	Kirstyn Johnson,	Caitlyn Cooke
2014	David Thomas,	John Kablubowski
2015	Esteban Rodriguez,	Ryan Montoya
2016	Ryan Montoya	Esteben Rodriguez

2017	Alec Weiss	Matthew Hurst
2018	Marika Schubert	Ryan Aronson
2019	Jacob Melonis	Cody Goldman

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

Student Paper Winners

2013 1st Place: Nicholas Truesdale, Kevin Dinkel, Jedediah Diller, Zachary Dischnew, "Daystar: Modeling and Testing a Daytime Star Tracker for High Altitude Balloon Observatories"

2nd Place: Christopher M. Pong, Kuo-Chia Liu, David W. Miller, "Angular Rate Estimation from Geomagnetic Field Measurements and Observability Singularity Avoidance during Detumbling and Sun Acquisition"

3rd Place: Gregory Eslinger, "Electromagnetic Formation Flight Control Using Dynamic Programming"

2014 1st Place: Dylan Conway, Brent Macomber, Kurt A. Cavalieri, John L. Junkins, "Vision-Based Relative Navigation Filter for Asteroid Rendezvous"

2nd Place: Robyn M. Woollands, John L. Junkins, "A New Solution for the General Lambert Problem"

3rd Place: Alex Perez, "Closed-Loop GN&C Linear Covariance Analysis for Mission Safety"

2015 1st Place: Andrew Liounis, Alexander Entrekin, Josh Gerhard, John Christian, "Performance Assessment of Horizon-Based Optical Navigation Techniques"

2nd Place: J. Micah Fry, "Aerodynamic Passive Attitude Control: A New Approach to Attitude Propagation and a Nano-satellite Application"

3rd Place: Siamak Hesar, Jeffrey S. Parker, Jay McMahon, George H. Born, "Small Body Gravity Field Estimation Using Liaison Supplemented Optical Navigation"

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

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

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

2017 1st Place: Simon Shuster, Andrew J. Sinclair, and T. Alan Lovell, "Uncertainty Analysis for Initial Relative Orbit Determination Using Time Difference of Arrival Measurements"

2nd Place: Himangshu Kalita, Ravi Teja Nallapu, Andrew Warren, and Jekan Thangavelautham, "Guidance, Navigation and Control of Multirobot Systems in Cooperative Cliff Climbing"

3rd Place: Max Rogovin and Brian Kester, "Two-Axis Stability of a High-Altitude Balloon Payload"

2018 1st Place: F. Franquiz, B. Udrea, M. Balas, "Optimal Rate Observability Trajectory Planning For Proximity Operations Using Angles-Only Navigation"

2nd Place: B. Bercovici, J. McMahon, "Autonomous Shape Determination Using Flash-Lidar Observations and Bezier Patches"

3rd Place: D. Jennings, J. Davis, P. Galchenko, H. Pernicka, "Validation of a GNC Algorithm Using a Stereoscopic Imaging Sensor to Conduct Close Proximity Operations"

2019 1st Place: A. Reynolds and H. Pernicka "Design and Verification of a Stereoscopic Imager for Use in Spacecraft Close Proximity Operations."

2nd Place: A. Boylston, J. Gaebler, and P. Axelrad "Extracting CubeSat Relative Motion Using In Situ Deployment Imagery"

3rd Place: G. Willburn, H. Kalita, A. Chandra, S. Schwartz, E. Asphaug, and J. Thangavelautham "Guidance Navigation and Control of Asteroid Mobile Imager and Geologic Observer (AMIGO)"

In 2015 the AAS Rocky Mountain Section partnered with the University of Colorado and hosted the inaugural STEM SCAPE conference on Saturday, which provided an introduction for the students to working in a STEM field and motivated them to pursue professional careers in aerospace engineering. This highly successful session brought in high school students, college students and included a design project, panel discussions, an opportunity to meet industry representatives, practice interviews for the college students and a keynote speech. This event was continued in 2016, building on the prior year and again reaching over 100 high school and college students.

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

	Conference Chair	**Attendance**
1978	Robert L. Gates	83
1979	Robert D. Culp	109
1980	Louis L. Morine	130
1981	Carl Henrikson	150
1982	W. Edwin Dorroh, Jr.	180
1983	Zubin Emsley	192
1984	Parker S. Stafford	203
1985	Charles A. Cullian	200
1986	John C. Durrett	186
1987	Terry Kelly	201
1988	Paul Shattuck	244
1989	Robert A. Lewis	201
1990	Arlo Gravseth	254
1991	James McQuerry	256
1992	Dick Zietz	258
1993	George Bickley	220
1994	Ron Rausch	182
1995	Jim Medbery	169
1996	Marv Odefey	186
1997	Stuart Wiens	192
1998	David Igli	189
1999	Doug Wiemer	188
2000	Eileen Dukes	199
2001	Charlie Schira	189
2002	Steve Jolly	151
2003	Ian Gravseth	178
2004	Jim Chapel	137
2005	Bill Frazier	140
2006	Steve Jolly	182

2007	Heidi Hallowell	206
2008	Michael Drews	189
2009	Ed Friedman	160
2010	Shawn McQuerry	189
2011	Kyle Miller	161
2012	Michael Osborne	139
2013	Lisa Hardaway	181
2014	Alexader May	180
2015	Ian Granvseth	195
2016	David Chart	216
2017	Reuben Rohrschneider	201
2018	Cheryl Walker	236
2019	Heidi Hallowell	215

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

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

On behalf of the Conference Committee and the Section,

Heidi Hallowell
Ball Aerospace
Boulder, Colorado

PREFACE

The 42nd annual AAS Guidance and Control Conference opened on the heels of a challenging final planning period during a government shutdown. The shutdown had been looming over the conference up to the week before its opening weekend, creating challenges for some authors to attend and risking some very short sessions. We were at the ready with a contingency plan should the government still be shut down at the conference opening. We were also looking to other conferences that had been affected for mitigation ideas while we considered our options to keep the conference moving forward in a format all would find valuable. So, one can imagine our relief when the shutdown ended and the conference was able to go on as planned, for the most part. Such is the turmoil that we often encounter in the aerospace industry as we strive for innovation and mission success.

As always, from our first planning meeting, we strived to present the hop topics of the day while keeping our more popular and well-attended sessions as mainstays from year to year. Advanced and autonomous navigation techniques was a forward-looking topic brought to our attention by long-time conference supporter Neil Dennehy of NASA. We have always appreciated friends of the conference bringing those ideas to the committee and highly encourage that kind of participation. Overall, our conference maintained the same format as the last couple of years, including tutorials between sessions, as this format has proven to be quite successful over the previous years. In the end, the program became a timely reflection of the current state of the space industry. We were also pleased that each session, even up to the very last one on the last morning, was well-attended. I would like to thank the planning committee for their dedication in putting together the conference, especially with the churn that ensued in the closing stages of the planning.

Thursday and Friday featured our classified sessions held at the Aerospace Corporation in Colorado Springs. These sessions have received excellent reviews from attendees and give industry professionals the opportunity to share at a level unavailable at our traditional conference.

Our regular conference opened Saturday morning, February 3 with Session I, "Student Innovations in GN&C", a topic which has held this spot for a few years now. It is an opportunity for students to present the latest in cutting edge research currently occurring in the university setting. The top 3 papers, judged by a panel of conference planning committee members and attendees, were presented with awards during our Technical Exhibits session. First place was awarded to A. Reynolds and H. Pernicka from Missouri University of Science and Technology for their paper on "Design and Verification of a Stereoscopic Imager for Use in Spacecraft Close Proximity Operations." A. Boylston, J. Gaebler, and P. Axelrad from the University of Colorado at Boulder took second place with "Extracting CubeSat Relative Motion Using In Situ Deployment Imagery". Finally, third place was awarded to G. Willburn, H. Kalita, A. Chandra, S. Schwartz, E. Asphaug, and J. Thangavelautham from the University of Arizona for their paper "Guidance Navigation and Control of Asteroid Mobile Imager and Geologic Observer (AMIGO)".

In parallel, the AAS STEM-Scape Event, going on its 4th year, gave high school students from Denver to Grand Junction an opportunity to experience a professional conference as they consider their future college experiences and careers. In addition to asking questions of a panel consisting of both young professionals and those who are further along in their careers, the students also participated in a design contest. Here, they had the opportunity to put their problem-solving skills to the test in a team environment.

That evening, attendees gathered for a conference favorite – “Technical Exhibits” (Session II). As you may recall, this session is as much social as it is technical, with conversation occurring over a buffet prepared by Beaver Run. As it is a family event, both young and adult attendees had the opportunity for one-on-one interaction with those in the forefront of the space industry’s future.

Sunday morning featured parallel sessions which addressed a growing trend toward smaller spacecraft as well as the challenges of operating spacecraft beyond the confines of Earth. Session III, “GN&C Challenges with Robotic Deep Space Exploration”, opened the day with papers which highlighted missions visiting somewhat closer destinations such as Mars and more far-flung object such as asteroids. Session IV, “Small Satellite GN&C” (another very relevant conference favorite) highlighted some of the challenges of placing traditional spacecraft functionality into a small package, sometimes resulting in a reduced sensor and hardware suite and limited to no propulsion capability. Some papers discussed small satellite usage beyond Earth orbit.

Our afternoon duo of shorter sessions included Session V, “Extended Mission Spacecraft” and Session VI, “GN&C Innovations”. Many spacecraft will go into extended mission phases, given enough fuel, hardware capability, and budget. Some programs will go to great lengths to eek out every bit of life even if there is a hardware failure. Cloudsat is one such spacecraft highlighted in a paper for this session. Kepler’s last bit of science collecting was also discussed in this session. “GN&C Innovations” featured a smaller collection of papers that highlighted a variety of GN&C challenges and innovations from the ISS to small satellites.

Our Monday morning program consisted of session dedicated to navigation and propulsion. Session VII, “Advanced Navigation Applications and Technologies” was new to the conference this year and addressed navigation technologies and methods driven by upcoming interplanetary deep space lunar, asteroid, and Martian missions. In addition, Session VIII, “Advanced Propulsion” was a returning conference favorite. We always find interesting topics here, including papers on steam and fission/fusion powered propulsion systems.

Monday afternoon wrapped up with Session IX, “Autonomous Navigation in the Earth-Moon System, and Session X, “Lessons Learned in GN&C Simulation, Verification, and Validation”. Our navigation session was a hot topic and encouraged relevant papers on NASA’s Lunar Orbital Platform-Gateway and related programs such as “The Cislunar Autonomous Positioning System (CAPS). In addition, the planning committee had really supported the lessons learned in Session X, given there was so much knowledge in the community to share on GN&C system testing.

Tuesday led off with two well-attended and traditional conference favorites: Session XI, “Advances in GN&C Software” and Session XII, “Advances in GN&C Hardware”. These sessions give attendees the opportunity to hear from those on the forefront of current and future innovations in the areas which form the very heart of a spacecraft program. Examples of topics in our software session included Lasercom and autonomous calibration of horizon sensors. Our hardware session included papers featured innovative twists on heritages solutions involving hardware such as star trackers and CMGs.

Session topics on Tuesday afternoon included two more very pertinent topics. Session XIII, “Space Observatory Line-of-Sight Jitter/Micro-Vibration” addressed the increasing demand for extremely quiet platforms for high-performance systems. Papers involving topics from GEO platforms to future interplanetary missions were presented. For Session XIV, “Formation Flying and Autonomy”, Michelle Miller, Ball Aerospace Director of Missions and Systems Engineering, gave a brief introduction. Topics from optimal trajectory design to swarm attitude control were presented.

The last day of the conference began with our traditional and popular “Recent Experiences” session. Having the chance to see real on-orbit data and listen to the experiences of those flying current or recently wrapped up programs have kept this session popular among our regular attendees. It is quite a treat to see what our colleagues have experienced on various programs to see what we might apply to our own efforts.

The 42nd Annual AAS Guidance and Control Conference was a success in all the ways the planning committee had hoped when we first began the planning process during the spring of 2018. Even though we could never have anticipated the last-minute challenges thrown our way, the dedication of our volunteers allowed the conference to continue as always. We still had our usual mix of current hot topics and traditional favorites which still showcase the innovation occurring in GN&C in our industry. In addition, our Technical exhibits session allowed attendees to mingle with other professionals they might not see on a regular basis. It is this mixture of technical and social interactions which makes this conference unique and keeps attendees coming back year after year.

I'd like to thank Amy Delay and Michelle Barath of Lockheed Martin Space and Lis Garratt of Ball Aerospace for organizing the conference meetings, attendee materials, and ensuring the conference ran smoothly.

Heidi Hallowell
Conference Chairperson
2019 AAS Guidance and Control Conference

CONTENTS

STUDENT INNOVATIONS IN GUIDANCE, NAVIGATION AND CONTROL

Session 1

National Chairpersons:

Luke Sauter, USAF

David Geller, Utah State University

Local Chairpersons:

Ian Gravseth, Ball Aerospace

Morgan Yost, Lockheed Martin Space Systems Company

The following papers were not available for publication:

AAS 19-012 (Paper Withdrawn)

AAS 19-018 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 19-001 to -010 and AAS 19-020 to -030

AAS 19-011

GUIDANCE, NAVIGATION AND CONTROL OF ASTEROID MOBILE IMAGER AND GEOLOGIC OBSERVER (AMIGO)

Greg Wilburn,[*] Himangshu Kalita,[†] Aman Chandra,[†] Stephen Schwartz,[‡] Erik Asphaug[§] and Jekan Thangavelautham[**]

The science and origins of asteroids is deemed high priority in the Planetary Science Decadal Survey. Major scientific goals for the study of planetesimals are to decipher geological processes in SSSBs not determinable from investigation via in situ experimentation, and to understand how planetesimals contribute to the formation of planets. Ground based observations are not sufficient to examine SSSBs, as they are only able to measure what is on the surface of the body; however, in situ analysis allows for further, close up investigation as to the surface characteristics and the inner composure of the body. To this end, the Asteroid Mobile Imager and Geologic Observer (AMIGO) an autonomous semi-inflatable robot will operate in a swarm to efficiently characterize the surface of an asteroid. The stowed package is 10×10×10 cm (equivalent to a 1U CubeSat) that deploys an inflatable sphere of ~1m in diameter. Three mobility modes are identified and designed: ballistic hopping, rotation during hops, and up-righting maneuvers. Ballistic hops provide the AMIGO robot the ability to explore a larger portion of the asteroid's surface to sample a larger area than a stationary lander. Rotation during the hop entails attitude control of the robot, utilizing propulsion and reaction wheel actuation. In the event of the robot tipping or not landing upright, a combination of thrusters and reaction wheels will correct the robot's attitude. The AMIGO propulsion system utilizes sublimate-based micro-electromechanical systems (MEMS) technology as a means of lightweight, low-thrust ballistic hopping and coarse attitude control. Each deployed AMIGO will hop across the surface of the asteroid multiple times. Individual actuation of each microvalve on the MEMS chip provides control torque for rough attitude control with only slight alteration to the hop path en-route to its destination. For optimal use of instrumentation, namely the top mounted stereo cameras utilized in local surface mapping and navigation planning, the robot must remain as upright as possible during data acquisition. Should AMIGO land in an improper orientation, thrusters and reaction wheels will attempt to correct the positioning. Several inflatable structures will be evaluated including a soft inflatable and an inflatable that rigidizes under UV light. The inflatable will be compared under operational scenarios to determine if it produces disturbances torque and an un-steady view for the stereo cameras. Future work is focused on raising the TRL by real world testing system performance and utilizing hardware-in-the-loop simulation models. The thruster assembly can be evaluated on a test stand mounted inside a vacuum chamber. To simulate milli-gravity, the entire robot will be analyzed in either parabolic flight tests or in buoyancy chambers. A combination of experimentation will validate simulations and provide insight in areas to improve on the design and control algorithms for milli-gravity asteroid surface environments. [View Full Paper]

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APPLICATION OF PREDICTIVE CONTROL FOR DESIRED ATTITUDE STABILIZATION WITH MAGNETIC ACTUATORS

Daniel Newberry,[*] Blakely Mayhall,[†] David Western,[†] Donna Jennings[*] and Henry Pernicka[‡]

A predictive controller was modified and applied to a microsatellite to show that attitude stabilization about two axes can be achieved using only magnetic actuators. The predictive controller is based on previous works by other authors with modifications for a spacecraft without gyroscopic stiffness. The system is described by a discrete-update law and uses a predictive control approach to calculate the control effort. In order to test the controller, a truth model using two-body dynamics and Euler's equations along with solar radiation pressure, atmospheric drag, and gravity gradient perturbations was developed. To analyze the fidelity of the controller, a Monte Carlo analysis was conducted and showed that all simulated scenarios achieved the desired attitude and attitude rates. In addition, power consumption, time to reach desired attitude, and state errors were analyzed.
[View Full Paper]

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AAS 19-014

DEVELOPMENT AND ANALYSIS OF NRHO RENDEZVOUS REFERENCE TRAJECTORIES USING CONVEX OPTIMIZATION

Simon Shuster*

Missions to the proposed Lunar Orbital Platform-Gateway will involve unique rendezvous and proximity operations challenges that directly impact the reference trajectory design. In this paper, sequential convex programming is applied to the design of far-field rendezvous reference trajectories for spacecraft in a Near-Rectilinear Halo Orbit. Trajectories that minimize Δv are obtained that satisfy approach corridor, free drift, underburn, velocity magnitude, and maneuver transfer time constraints. A trade study is performed to analyze the sensitivity of the velocity magnitude constraint to the Δv budget. This analysis is repeated for different initial conditions and fixed-final times. [View Full Paper]

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AAS 19-015

DESIGN AND VERIFICATION OF A STEREOSCOPIC IMAGER FOR USE IN SPACE CLOSE PROXIMITY OPERATIONS

Alex Reynolds[*] and Henry Pernicka[†]

Stereoscopic imaging presents an exciting, low-cost alternative to traditional methods of relative navigation for small satellites. This paper discusses the development and testing of a fast, effective computer vision algorithm for such a case. A brief overview of the MR SAT microsatellite and its stereoscopic imaging hard-ware is presented, followed by an in-depth discussion of the software development. The FAST, SURF, and FLANN computer vision algorithms employed in the imaging algorithm are detailed, and methods for reducing navigational errors in the space environment are developed. Results from laboratory testing and Systems Tool Kit (STK) simulations are presented, and imager performance is evaluated. [View Full Paper]

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AAS 19-016

EXTRACTING CUBESAT RELATIVE MOTION USING IN SITU DEPLOYMENT IMAGERY

Adam Boylston,* John Gaebler† and Penina Axelrad‡

Analyzing videos of CubeSat deployments can reveal crucial information about the order of deployment and orbital parameters of each CubeSat. By using downlinked videos the data could be available within minutes, compared to the hours it can take to get radar data. Previous efforts have attempted to find range of a single CubeSat, however there needs to be an approach to handle deployments of multiple satellites. In this paper we introduce a new technique that works for any number of satellites without the need for a calibrated camera. The proposed method includes autonomous CubeSat detection, using the known size and shape of CubeSats to fit 3D cuboids to a 2D image, and using camera properties to determine depth and relative distances of the CubeSats. [View Full Paper]

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AAS 19-017

MOTION PLANNING ON AN ASTEROID SURFACE WITH IRREGULAR GRAVITY FIELDS

Himangshu Kalita[*] and Jekan Thangavelautham[†]

There are thousands of asteroids in near-Earth space and millions in the Main Belt. They are diverse in physical properties and composition and are time capsules of the early solar system. This makes them strategic locations for planetary science, resource mining, planetary defense/security and as interplanetary depots and communication relays. However, asteroids are a challenging target for surface exploration due it its low but highly nonlinear gravity field. In such conditions, mobility through ballistic hopping possess multiple advantages over conventional mobility solutions and as such hopping robots have emerged as a promising platform for future exploration of asteroids and comets. They can traverse large distances over rough terrain with the expenditure of minimum energy. In this paper we present ballistic hopping dynamics and its motion planning on an asteroid surface with highly nonlinear gravity fields. We do it by solving Lambert's orbital boundary value problem in irregular gravity fields by a shooting method to find the initial velocity required to intercept a target. We then present methods to localize the hopping robot using pose estimation by successive scan matching with a 3D laser scanner. Using the above results, we provide methods for motion planning on the asteroid surface over long distances. The robot will require to perform multiple hops to reach a desired goal from its initial position while avoiding obstacles. The study is then extended to find optimal trajectories to reach a desired goal by visiting multiple waypoints.

[View Full Paper]

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VISUAL AND THERMODYNAMIC ANALYSIS OF POLYMETHYL METHACRYLATE COMBUSTION IN HYBRID ROCKETS

Megan Langas,[*] Gordon McCulloh,[*] James Rice,[*] Connor Brazinski,[*] Sarah Gingras,[*] Timothy Lloyd,[*] Alejandro Villanueva[*] and David Cunningham[†]

This paper presents the results of a hybrid rocket test campaign to quantify important combustion parameters of solid polymethyl methacrylate (PMMA) fuel and gaseous oxygen oxidizer. The aims of the research described here are 1) develop a method to measure PMMA regression rate, 2) minimize wasted fuel at the end of firing, and 3) produce thermal and high speed visual imagery of the combustion chamber for further analysis. Previous research in this area was conducted at NASA's Jet Propulsion Laboratory (JPL) found that regression rates of the PMMA were high enough that chamber pressure increased during test firings, while accepted values model a lower regression rate leading to reduction in chamber pressure during a burn. Research at USAFA is being conducted on a thrust chamber assembly designed, manufactured, and built by students. Thrust chamber geometry is similar to the JPL setup, but USAFA testing occurred at lower chamber pressure and oxidizer mass flow rates than many of the JPL tests. Additionally, the USAFA test cell is not enclosed and only transparent PMMA is used, facilitating real-time visualization of the combustion. Different injector assemblies lend themselves to varying flow characteristics. High speed imagery of combustion allowed rudimentary visualization of flow structures and mixing during combustion, facilitating future improvements in both fuel utilization and efficiency. First, chamber pressure data was obtained from multiple test firings that, in conjunction with increased control of the oxidizer mass flow rate via a newly designed sonic nozzle choking the oxygen flow upstream of combustion, allowed for characterization of the PMMA regression rate. Results proved more in line with a new nonlinear JPL method of determining combustion coefficients than the previously used linear method, though not enough data has been collected to be conclusive. Future work will include injector design improvements to facilitate improved mixing, increased test data for regression analysis, and nozzle analysis; as well as more detailed flow visualization to allow characterization of transient combustion phenomena.
[View Full Paper]

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GUIDANCE, NAVIGATION AND CONTROL CHALLENGES WITH ROBOTIC DEEP SPACE EXPLORATION

Session 3

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Local Chairpersons:

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Larry Germann, Left Hand Design Corporation

The following paper numbers were not assigned:

AAS 19-038 to -040

AAS 19-031

AN AUTONOMOUS PASSIVE NAVIGATION METHOD FOR NANOSATELLITE EXPLORATION OF THE ASTEROID BELT

Leonard Vance,* Jekan Thangavelautham† and Erik Asphaug‡

There are more than 750,000 asteroids identified in the main belt. These asteroids are diverse in composition and size. Some of these asteroids can be traced back to the early solar system and can provide insight into the origins of the so-lar system, origins of Earth and origins of life. Apart from being important tar-gets for science exploration, asteroids are strategically placed due to their low-gravity well, making it low-cost to transport material onto and way from them. They hold valuable resources such as water, carbon, metals including iron, nick-el and platinum to name a few. These resources maybe used in refueling depots for interplanetary spacecraft and construction material for future space colonies, communication relays and space telescopes. The costs of getting to the main asteroid belt, combined with large numbers of objects to be explored encourage the application of small spacecraft swarms. The size and capability of the resulting nano-spacecraft can make detection from Earth difficult. This paper dis-cusses a method by which a spacecraft can establish ephemeris autonomously using line of sight measurements to nearby asteroids with Extended Kalman Filtering techniques, without knowing accurate ephemeris of either the asteroids or the spacecraft initially. A description of the filter implementation is followed by examples of resultant performance.

[View Full Paper]

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AAS 19-032

LIDAR-GENERATED DIGITAL ELEVATION MODELS FOR HAZARD DETECTION - REQUIREMENTS AND ANALYSIS

Po-Ting Chen,* Siddarth Kaki,† A. Miguel San Martin,‡ David Skulsky,§ Anup Katake and Nikolas Trawny††**

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Hazard detection is an enabling technology for safe landing on planetary bodies with limited terrain knowledge, such as Jupiter's icy moon Europa. Using a Light Detection and Ranging (LIDAR) sensor, a lander scans the landing site and constructs a Digital Elevation Model (DEM) in real-time during descent. This DEM is processed by hazard detection algorithms to construct a safety cost map and determine the safest landing location. The target location is then provided to the guidance and control system to execute a hazard avoidance divert maneuver. We derived requirements on the DEM quality and accuracy from the proposed Europa Lander Deorbit, Descent, and Landing (DDL) concept of operations and the lander hazard tolerance. A modular geometric LIDAR modeling tool and re-gridding algorithms were developed and integrated into a high-fidelity 6-DOF dynamics simulation. The modular nature of the model allows us to simulate various detector aspect ratios, laser pulse repetition rates, scan mechanisms, optical designs, and basic error models. This tool was developed to support the parametric sensitivity analysis of the DEM quality with respect to the LIDAR design, site topography, scanning pattern, noise properties, and navigation state knowledge errors, and to evaluate the generated DEMs against the Europa Lander requirements. [View Full Paper]

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AAS 19-033

GUIDANCE, NAVIGATION, AND CONTROL FOR NASA LUNAR PALLET LANDER

Juan Orphee,[*] Mike Hannan,[†]
Naeem Ahmad,[*] Evan Anzalone,[*] Ellen Braden,[‡] Scott Craig,[*]
Jason Everett,[*] Kyle Miller[*] and Nicholas Olson[*]

The NASA Lander Technology project is leading the development and integration of the Lunar Pallet Lander (LPL) concept. The objective is to demonstrate precision landing by delivering a payload to the lunar surface within 100 meters of a landing target. Potential landing sites are selected near the lunar pole where water may be present in permanently shadowed regions that could enable future in-situ resource utilization. The LPL is part of a sequence of missions aimed at maturing the necessary technologies, such as lunar precision landing sensors, that will enable the next generation of multi-ton lunar payloads and human landers. This paper provides an overview of the Mission Design, Guidance Navigation and Control (GNC) algorithms, and sensor suite. The results show the LPL simulated trajectory and landing precision performance under nominal and dispersed conditions. The landing precision simulation confirms the need to rely on high-accuracy navigation instruments such as Terrain Relative Navigation (TRN) and Navigation Doppler Lidar (NDL). The results also demonstrate the ability of the guidance and control system to perform a soft lunar touchdown by combining thrust vector control during the solid rocket motor deceleration phase, and pulse engine control for the liquid powered descent phase. [View Full Paper]

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AAS 19-034

GUIDANCE AND NAVIGATION DESIGN FOR A MARTIAN SAMPLE RETURN ASCENT VEHICLE

Evan Anzalone,[*] Dane Erickson[†] and Carlos Montalvo[‡]

This paper focuses on the work being performed at the NASA Marshall Space Flight Center (MSFC) in support of Mars Ascent Vehicles (MAVs). Specifically, the analysis presented is in support of Martian sample return architectures. In order to assess vehicle sensitivities, a detailed simulation tool, (MAV Analysis Tool in Simscape) MANTIS, was implemented using the MATLAB/Simulink Simscape architecture. High fidelity navigation sensor models and guidance algorithms were included in order to facilitate sensor requirement development and flight algorithm selection. This work focuses on the performance of the integrated system and the coupling of navigation and guidance capabilities. The architecture trades are heavily dependent on the ascent flight profile chosen. This work assesses both open- and closed-loop guidance algorithms to capture their relative performance and the resulting requirements on sensor capability to support preliminary vehicle design. The analysis builds on previous work that focused on navigation performance for initialization and ascent flight of crewed vehicle. The results provide insight into the coupling between sensor requirements and ascent guidance approach. The analysis provides data to support requirements for hardware selection and testing. Additional discussion is also included focusing on other system constraints that affect hardware selection and operational constraints. [View Full Paper]

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AAS 19-035

EARLY NAVIGATION PERFORMANCE OF THE OSIRIS-REX APPROACH TO BENNU

Peter G. Antreasian,[*] Michael C. Moreau,[†] Coralie D. Adam,[*] Andrew French,[*] Jeroen Geeraert,[*] Kenneth M. Getzandanner,[†] Dolan E. Highsmith,[‡] Jason M. Leonard,[*] Erik Lessac-Chenen,[*] Andrew Levine,[*] Jim McAdams,[*] Leilah McCarthy,[*] Derek Nelson,[*] Brian Page,[*] John Pelgrift,[*] Samantha Rieger,[†] Eric Sahr,[*] Daniel Wibben,[*] Bobby Williams,[*] Kenneth Williams,[*] Dante Lauretta[§] and the OSIRIS-REx Team.

The New Frontiers–class OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security–Regolith Explorer) mission is the first American endeavor to return a sample from an asteroid. In preparation for retrieving the sample, OSIRIS-REx is conducting a campaign of challenging proximity-operations maneuvers and scientific observations, bringing the spacecraft closer and closer to the surface of near-Earth asteroid (101955) Bennu. Ultimately, the spacecraft will enter a 900-meter-radius orbit about Bennu and conduct a series of reconnaissance flybys of candidate sample sites before being guided into contact with the surface for the Touch and Go sample collection event. Between August and December 2018, the OSIRIS-REx team acquired the first optical observations of Bennu and used them for navigation. We conducted a series of maneuvers with the main engine, Trajectory Correction Maneuver, and Attitude Control System thruster sets to slow the OSIRIS-REx approach to Bennu and achieve rendezvous on December 3, 2018. This paper describes the trajectory design, navigation conops, and key navigation results from the Approach phase of the OSIRIS-REx mission. [View Full Paper]

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DEMONSTRATION OF STEREO VISION FOR DEORBIT DESCENT AND LANDING*

David C. Sternberg,† Timothy P. Setterfield,‡ Erik S. Bailey,§ Adnan I. Ansar and Andrew E. Johnson††**

Planetary landers need to reduce velocity at low altitude for soft landing. Traditionally, estimating velocity and altitude has been performed with radar sensors whose performance meets the specific mission needs. There are not very many options for these sensors and they are difficult to include in a flight system either due to obsolescence, prohibitive cost or difficulty in accommodation. Recently, alternative sensing modalities are being pursued including Doppler LiDAR and vision. This paper describes results from a recent helicopter field test of a binocular stereo vision system for deorbit descent and landing applications. The system consisted of two 18.6˚ field of view cameras mounted 1.7m apart. Post processing of the images showed ranging accuracy better than 1% up to 500m and 17 cm/s velocimetry accuracy at 37m. For a flight system these images could be input into an FPGA-based processor which processes dense stereo and visual odometry in less than 1 second to achieve the stereo ranging frame rates required for soft landing. When coupled with vision based Terrain Relative Navigation this stereo system enables landing accuracies on the order of 10m. [View Full Paper]

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AAS 19-037

ARCHITECTURE OF A FAULT-TOLERANT AND VERIFIABLE OUTER PLANET FLYBY[*]

William Frazier,[†] Eric Rice[†] and Karl L. Mitchell[†]

Flyby missions to outer solar system objects require a very high confidence of success since there are no second chances. The quantity, quality, and diversity of science measurements to be made in a matter of hours or days must justify the mission cost. Accordingly, the mission architecture must include a high degree of redundancy, large design margins, and an ability to correct or operate through anomalies while at the same time being deterministic enough for confidence in system verification and validation. In this paper we pre-sent a system architecture as part of a proposed mission to Triton, called "Trident". The concept includes multiple layers of insurance against one or more failures while still achieving a successful flyby. Elements of this robustness include: flyby mission design, large timing margins built into the encounter sequence, multiple redundant science observations with adequate data storage, an instrument suite providing overlapping measurements, active redundancy, and conservative GN&C design. We develop the sequence de-sign with an eye to fault management architecture to minimize interactions and avoid extra complexity. The software-controlled fault protection scope is limited to targeted failure responses during encounter at the component level where possible and at the system level only when necessary, and is enabled by an integrated system architecture that ensures robustness during critical operations. The design is intended to be easily verifiable in system test without the need to exercise a large number of permutations or interactions between fault responses. [View Full Paper]

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SMALL SATELLITE GUIDANCE, NAVIGATION AND CONTROL

Session 4

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Tom Segal, Metropolitan State University, Denver

The following papers were not available for publication:

AAS 19-042 (Paper Withdrawn)

AAS 19-047 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 19-049 to -050

AAS 19-041

IMPROVING ORBIT DETERMINATION OF CLUSTERED CUBESAT DEPLOYMENTS USING CAMERA-DERIVED OBSERVATIONS

John A. Gaebler[*] and Penina Axelrad[†]

Orbit determination of LEO satellites using ground-based radar tracking is well-established as the standard for maintaining situational awareness. It provides sufficient accuracy to support a space catalog and produce two-line element sets (TLEs). One scenario that still poses a challenge for ground-based observers is a clustered CubeSat deployment. Camera-based observations of deploying CubeSats are simulated to improve early orbit determination. A simulation of the Planet Labs deployment of 88 CubeSats from PSLV-C37 launch demonstrates the approach. [View Full Paper]

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AAS 19-043

ADVANCED ALGORITHM AND DESIGN IMPLEMENTATIONS FOR SMALL SPACECRAFT GN&C

Matthew Baumgart, Michael Ferenc, Bryan Rogler, Devon Sanders*

Driven by paradigm-shifting cost savings, the scope of small spacecraft missions continues to quickly expand in terms of both spacecraft quantity and required system performance/capability. Examples include the MarCO cubesats (interplanetary mission), ASTERIA cubesat (sub-arcsecond pointing performance), and spacecraft constellations such as the CYGNSS weather observatories. At the same time, program schedules are typically compressed versus traditional large space efforts, and mission budgets for design, I&T, and spacecraft operations are often very lean to reflect the reduced overall mission budget. Given these factors, the launch-time uncertainty in system physical parameters (mass, inertia, flexible modes, alignments, etc.) may be higher than for traditional space programs, while at the same time an increased level of autonomy is required to perform complex missions with a minimal level of ground support. These challenges, along with the relatively high computational capability of small spacecraft processors and opportunity for extensive software re-use, incentivize rapid development and deployment of advanced GN&C software algorithms and design tools. Short program schedules also offer the opportunity to quickly validate new approaches and algorithms on flight missions. This paper presents some recent implementations in these areas for small spacecraft missions: autonomous online nonlinear optimization (for increased spacecraft autonomy and performance), and rapid high-performance attitude controller design via multi-channel optimization (to maximize performance in the face of limited ground testing). These implementations emerge where the constraints of small spacecraft programs drive an outsized benefit from investments in software capability and standardized design/analysis/test infrastructure. [View Full Paper]

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SMALL SPACECRAFT STATE OF THE ART IN GUIDANCE, NAVIGATION, AND CONTROL

Bruce D. Yost*

The advancement of small spacecraft systems and concepts is an ongoing interest in the space community as advanced technology continues to develop to support innovative space science exploration. The Small Spacecraft Systems Virtual Institute (S3VI) identifies emerging small spacecraft technology and opportunities to facilitate the collaboration and dissemination of research results that is relevant to promoting space science research. This paper highlights the components of the Guidance, Navigation & Control (GNC) subsystem of small spacecraft and provides specific performance characteristics and Technology Readiness Level (TRL) values for each component. The content below is not intended to be exhaustive but a snapshot of current small spacecraft GNC capabilities.

A key element of S3VI's charter is that it serves to provide the small spacecraft research community at large with access to mission enabling information. Through a collaboration with the Air Force Research Laboratory and Space Dynamics Laboratory, the S3VI supports the continued development and management of a small spacecraft parts database called SmallSat Parts On Orbit Now (SPOON) that hosts performance and technical specifications for parts and technologies developed by industry, academia and government. The Small Spacecraft Technology State of the Art report encompasses select small spacecraft parts submitted to the SPOON database along with parts compiled from other sources determined to be in the class representing the current state of the art of small spacecraft technologies in each of the major subsystems. The 2018 State of the Art survey results in the guidance, navigation, and control subsystem for small spacecraft will be presented. [View Full Paper]

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ATTITUDE CONTROL OF AN INFLATABLE SAILPLANE FOR MARS EXPLORATION

Adrien Bouskela,* Aman Chandra,*
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Exploration of Mars has been made possible using a series of landers, rovers and orbiters. The HiRise camera on the Mars Reconnaissance Orbiter (MRO) has captured high-resolution images covering large tracts of the surface. However, orbital images lack the depth and rich detail obtained from in-situ exploration. Rovers such as Mars Science Laboratory and upcoming Mars 2020 carry state-of-the-art science laboratories to perform in-situ exploration and analysis. However, they can only cover a small area of Mars through the course of their mission. A critical capability gap exists in our ability to image, provide services and explore large tracts of the surface of Mars required for enabling a future human mission. A promising solution is to develop a reconnaissance sailplane that travels tens to hundreds of kilometers per sol. The aircraft would be equipped with imagers that provide that in-situ depth of field, with coverage comparable to orbital assets such as MRO. A major challenge is that the Martian carbon dioxide atmosphere is thin, with a pressure of 1% of Earth at sea level. To compensate, the aircraft needs to fly at high-velocities and have sufficiently large wing area to generate the required lift. Inflatable wings are an excellent choice as they have the lowest mass and can be used to change shape (morph) depending on aerodynamic or control requirements. In this paper, we present our design of an inflatable sailplane capable of deploying from a 12U CubeSat platform. A pneumatic deployment mechanism ensures highly compact stowage volumes and minimizes complexity. The present work attempts to describe expected dynamic behavior of the design and contributes to evolving an effective strategy for attitude control required for stable flight and high-quality imaging. The use of Dynamic Soaring as a means of sustained unpowered flight in the low-density Martian atmosphere will be studied through a point mass sailplane model. Using a linear wind gradient model of the Martian atmospheric boundary layer, numerical simulations of such trajectories will attempt to demonstrate that longer duration missions can be conducted using such hardware and flight characteristics. [View Full Paper]

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AAS 19-046

GNC CHALLENGES AND OPPORTUNITIES OF CUBESAT SCIENCE MISSIONS DEPLOYED FROM THE LUNAR GATEWAY

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The Lunar Gateway is expected to be positioned on-orbit around the Moon or in a Halo orbit at the L2 Lagrange point. The proposed Lunar Gateway is a game-changer for enabling new, high-priority lunar science utilizing CubeSats and presents a refreshing new opportunity for utilization of these small spacecraft as explorers. In context, CubeSats are being stretched to their limits as interplanetary explorers. The main technological hurdles include high-bandwidth communications and reliable high delta-v propulsion. Advances in deep-space attitude determination and control has been made possible from the recent NASA JPL MarCO missions. Due to these limitations, CubeSats are primarily de-signed to be dropped-off from a larger mission. The limited mass and volume have required compromises of the onboard science instruments, longer wait times to send back science data to Earth, shorter mission durations or higher accepted risk. With the Lunar Gateway being planned to be closer to the Moon, it will provide significant savings for a propulsion system and provide a primary relay for communication apart from the DSN and enable tele-operated command/control. These three factors can simplify the mission enabling routine deployment of CubeSats into lunar orbit and enable surface missions. In this paper, we present preliminary designs of 2 CubeSat lunar lander design that will explorer lunar pits, Mare Tranquilitatis and the remnant magnetic fields Reiner Gamma.

[View Full Paper]

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AAS 19-048

HONEYWELL 3-AXIS HG4934 SPACE RATE SENSOR FOR SMALL SATELLITES*

Donald P. Horkheimer†

Recent industry trends show significant growth in the small satellite market. To date small satellite developers have been faced with the di-lemma when selecting an Inertial Reference Unit (3-axis rate sensor) of using legacy Space Qualified solutions with known performance and reliability, but with prohibitive Size, Weight, Power, and Cost (SWAP-C) or selecting unproven and untested off the shelf solutions with more favorable SWAP-C. The solution to the satellite developer's dilemma is Honeywell's new HG4934 Space Rate Sensor.

The HG4934SRS is derived from Honeywell's highly successful Micro Electro-Mechanical Systems (MEMS) based on the HG1930 and HG4930 Inertial Measurement Unit (IMU) family. The HG4934SRS has the same form factor as the HG1930 and is manufactured on the same high-volume production line. The HG4934SRS was developed especially for the Space environment utilizing Honeywell's extensive experience developing Space systems. Key components of the HG4930 were upgraded or replaced to create a product with known and proven capabilities in the Space environment, while retaining SWAP-C ad-vantages of MEMS sensors.

This paper introduces the soon to be qualified HG4934SRS, including its design characteristics, features, and performance. [View Full Paper]

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EXTENDED MISSION SPACECRAFT

Session 5

National Chairpersons:

Bill Frazier, NASA Jet Propulsion Laboratory

Tooraj Kia, NASA Jet Propulsion Laboratory

Local Chairperson:

Scott Mitchell, Ball Aerospace

Michael Osborne, Lockheed Martin Space Systems Company

The following paper numbers were not assigned:

AAS 19-057 to -060

AAS 19-051

CLOUDSAT – DEVELOPMENT OF A THRUSTER ONLY MANEUVERING AND DELTA-V CAPABILITY

Ian J. Gravseth* and Heidi E. Hallowell*

Since its launch in April 2006, the CloudSat spacecraft has been operating for 12 years, well beyond its 22-month design launch. Aging effects on the vehicle have recently forced changes in its operating strategy and led to a decision by NASA and JPL that it should exit the A-Train spacecraft constellation. Reliably exiting the A-Train while not endangering other spacecraft required two significant orbit lowering burns within a few hours of each other and separated by a change in true anomaly. Successful burns lowered the apogee and perigee below the A-Train altitude.

CloudSat's current battery limitations require that the reaction wheels and most of the bus components are powered off during eclipse. Performing delta-V's in our new mode of operations requires turning on the wheels at eclipse exit and using them to maneuver the vehicle to the burn attitude and post-burn maneuvering the vehicle for eclipse entry preparations. However, due to a likely relay issue on one of the remaining three operational reaction wheels, there was an increased risk that the problematic wheel wouldn't power on at eclipse exit or power off during eclipse, and either event would likely cause the vehicle to fault, enter safe mode and not execute the burns. If the first burn was executed and the second one was aborted, CloudSat would have a significantly different synodic period than the rest of the vehicles in the A-Train, and would rapidly exit its control box and encroach on the other vehicles in the A-Train.

In order to reduce the risk associated with the A-Train exit burns, a thruster only maneuvering capability was designed, tested and executed on CloudSat. For this set of burns, the delta-V thrusters were used to capture attitude at eclipse exit and maneuver to the burn attitude while meeting all the vehicle's other maneuver constraints including, the payload sun exposure requirements, the minimum solar array fraction requirements, keeping a three-axis attitude solution available for the maneuvers and ensuring that the two star trackers were clear of the Earth, sun and moon while executing the burns. This technique was developed and implemented onboard the vehicle, and this approach was used to successfully exit the A-Train on February 22nd, 2018. It was also subsequently used to further lower the vehicle's orbit while the team was developing a workaround for the reaction wheel relay issue. This paper will discuss the design of the thruster only attitude control and maneuvering, on-orbit testing of this capability, and the execution and performance of the thruster only burns. [View Full Paper]

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AAS 19-052

ALL STELLAR ATTITUDE DETERMINATION IMPLEMENTATION ON MARS RECONNAISSANCE ORBITER*

B. T. Mihevc,† E. Schmitz† and P. Travis†

The Mars Reconnaissance Orbiter (MRO) was launched in 2005 with a 2-year mission to survey and study the Martian terrain and atmosphere. Thirteen years and four extended missions later, challenges with aging hardware are driving innovative solutions to keep the orbiter functioning in its relay role. Initially required to last for 5.4 years, MRO was designed to survive 10 years. Originally, the mission obtained attitude rate information from Inertial Measurement Units (IMU) and attitude position information from star trackers through all mission phases. Already, operations past design life has resulted in the degradation of one IMU. To preserve life on the remaining IMU, MRO has developed and deployed an "All Stellar Patch" to begin obtaining attitude and attitude rate information from star trackers enabling operators to power off the remaining IMU during nominal operations. This paper details the transition to All Stellar Attitude Determination and its effects on MRO Operations. MRO has been flying with both IMUs powered off since March 19, 2018 – a feat that will enable MRO to support future Mars missions for nearly a decade longer. [View Full Paper]

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AAS 19-053

FAST ATTITUDE MANEUVERS FOR THE LUNAR RECONNAISSANCE ORBITER

Mark Karpenko,[*] Travis Lippman,[†] I. Michael Ross,[‡] Julie K. Halverson,[§] Timothy McClanahan,[**] Michael Barker,[††] Erwan Mazarico,[††] Rebecca Besser,[‡‡] Cornelius J. Dennehy,[§§] Tannen VanZwieten[***] and Aron Wolf[†††]

This paper describes a new operational capability for fast attitude maneuvering that is being developed for the Lunar Reconnaissance Orbiter (LRO). The LRO hosts seven scientific instruments. For some instruments, it is necessary to perform large off-nadir slews to collect scientific data. The accessibility of off-nadir science targets has been limited by slew rates and/or occultation, thermal and power constraints along the standard slew path. The new fast maneuver (Fast-Man) algorithm employs a slew path that autonomously avoids constraint violations while simultaneously minimizing the slew time. The Fast-Man algorithm will open regions of observation that were not previously feasible and improve the overall science return for LRO's extended mission. The design of an example fast maneuver for LRO's Lunar Orbiter Laser Altimeter that reduces the slew time by nearly 40% is presented. Pre-flight, ground-test, end-to-end tests are also presented to demonstrate the readiness of FastMan. This pioneering work is extensible and has potential to improve the science data collection return of other NASA spacecraft, especially those observatories in extended mission phases where new applications are proposed to expand their utility. [View Full Paper]

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AAS 19-054

THE K2 MISSION'S FINAL CAMPAIGNS: EXTENDING SCIENCE COLLECTION THROUGH OPERATIONS AND CONTROLS APPROACHES

Katelynn M. McCalmont-Everton,[*] Kipp A. Larson[†] and Colin A. Peterson[‡]

The Kepler spacecraft was designed for a 3.5 year prime mission lifetime through NASA's Discovery program. Kepler is now in its 10th year of operations and in its second mission: K2. The new paradigm of operations carries out science campaigns studying astrophysical targets by inertially pointing in the ecliptic for up to 85 days at a time. As of October 2018, 19 K2 science campaigns have successfully been completed and the data has been downlinked. New methods of evaluating fuel exhaustion and preservation have been paramount to maximizing the science return in the final months of the Kepler mission. This paper will examine the use of newly developed and deployed operational modes to extend Kepler's lifetime, enabling these recent science campaigns.

[View Full Paper]

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AAS 19-055

SMAP SCIENCE RECOVERY EFFORTS*

Christopher G. Ballard†

The Soil Moisture Active Passive (SMAP) spacecraft launched in January 2015, with a mission to produce global soil moisture maps every 1.5 days using a combination of active (radar) and passive (radiometer) L-band measurements. In July 2015, after 2.5 months in operation, the radar failed and was not able to transmit. While the radiometer was still producing excellent science measurements, the need to recover key active-passive soil moisture requirements was paramount. To that end, the science team found that the European Space Agency (ESA) had recently launched a C-band SAR spacecraft called Sentinel-1A (launched April 2014) in a similar orbit, which was seen as a potential replacement to the "active" part of the SMAP measurements. An analysis was performed to see what the resulting spatial and temporal coverage could be. The promising results of that coupled with the ramp up in global coverage from Sentinel-1A and 1B (launched April 2016) allowed SMAP to create a new joint science data product that strives to meet the original mission objectives. The joint product is now part of the routine release of SMAP data to the science community as of June 2018. [View Full Paper]

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AAS 19-056

SUOMI NPP (S-NPP) ON ORBIT PERFORMANCE SUMMARY

**Richard Brewster,[*] Bradley Hood,[†] Everett Hamilton,[‡]
Richard Burns,[§] Dylan States[**] and Steven Silva[††]**

This paper provides an overview of the Suomi-National Polar Partnership (S-NPP) on-orbit performance since launch in 2011. Throughout the seven years of on-orbit operations, the S-NPP bus has operated at 99.82% availability. S-NPP was originally procured as a proof of concept satellite for Joint Polar Satellite System constellation. But, with delays and on-orbit requirement changes, S-NPP became the stop-gap in operational weather data between aging missions of NASA's Earth Observing System (EOS) and NOAA's Joint Polar Satellite System. In May 2014, S-NPP became the Prime PM weather mission for NASA / NOAA. S-NPP remains the prime PM weather mission as of January 2019.
[View Full Paper]

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GUIDANCE, NAVIGATION AND CONTROL INNOVATIONS

Session 6

National Chairpersons:

Bill Frazier, NASA Jet Propulsion Laboratory

Paul Graven, Cateni

Local Chairperson:

Cheryl Walker, Parsons

The following papers were not available for publication:

AAS 19-062 “Recent Flight Experiences of Blue Canyon Technologies Spacecraft, ADCS, and Components,” by B. Rogler, M. Baumgart, M. Ferenc, D. Sanders (Blue Canyon Technologies). This was the only Poster Paper presented at the conference, so it was placed in Session 6. This was a presentation-only paper, and no written paper was available for publication.

AAS 19-063 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 19-066 to -070

AAS 19-061

TRAJECTORY CHARACTERISTICS OF SPACECRAFT PROPELLED BY A GROUND-BASED PLP SYSTEM ABOUT A NON-SPHERICAL CENTRAL BODY

Ya-Ling Wen* and Fu-Yuen Hsiao†

This paper studies the trajectory characteristics of the spacecraft propelled by a ground-based photonic laser propulsion (PLP) system about a non-spherical central body. In 2016, Prof. Stephen Hawking and some other scientists proposed a potential method to realize the interstellar flight and explore the Alpha Centauri system. In his vision, a tiny spacecraft will be propelled by a ground based PLP system, and kept accelerating to a very high speed. Since 2011 the trajectories of the PLP driven spacecraft have been studied for the past years, including using an airborne PLP system and a ground-based PLP system on a spherical central body. This paper extends the investigation to a ground-based PLP system on a non-spherical central body. The equations of motion of the spacecraft in the body-fixed frame is derived, and the corresponded Jacobi integral is found. Contours of zero-velocity lines are presented and trajectories of example missions will be provided as potential applications in the final paper. [View Full Paper]

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AAS 19-064

SEXTANT NAVIGATION ON THE INTERNATIONAL SPACE STATION: A HUMAN SPACE EXPLORATION DEMO

Greg N. Holt[*] and Brandon Wood[†]

Astronauts on board the International Space Station (ISS) tested a hand-held sextant to demonstrate potential use on future human exploration missions such as Orion and Gateway. The investigation, designed to aid in the development of emergency navigation methods for future crewed spacecraft, took place from June-December 2018. A sextant provides manual capability to perform star / planet-limb sightings and estimate vehicle state during loss of communication or other contingencies. Its simplicity and independence from primary systems make it useful as an emergency survival backup or confirming measurement source. The concept of using a sextant has heritage in Gemini, Apollo, and Skylab. This paper discusses the instrument selection, flight certification, crew training, product development, experiment execution, and data analysis. Preflight training consisted of a hands-on session with the instrument and practice in a Cupola mock-up with star field projector dome. The experiment itself consisted of several sessions with sextant sightings in the ISS Cupola module by two crew members. Sightings were taken on star pairs, star/moon limb, and moon diameter. The sessions were designed to demonstrate star identification and acquisition, sighting stability, accuracy, and lunar sights. Results are presented which demonstrate sightings within the accuracy goal of 60 arcseconds, even in the presence of window refraction effects and minimal crew training. The crew members provided valuable feedback on sighting products and microgravity stability techniques. [View Full Paper]

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AAS 19-065

RAPID DEVELOPMENT OF THE SEEKER FREE-FLYING INSPECTOR GUIDANCE, NAVIGATION, AND CONTROL SYSTEM

Jacob Sullivan,[*] Elisabeth Gambone,[*] Thomas Kirven,[†]
Samuel Pedrotty,[*] and Brandon Wood[*]

Seeker is an automated extravehicular free-flying inspector CubeSat designed and built in-house at the Johnson Space Center (JSC). As a Class 1E project funded by the International Space Station (ISS) Program, Seeker had a streamlined process to flight certification, but the vehicle had to be designed, developed, tested, and delivered within approximately one year after authority to proceed (ATP) and within a $1.8 million budget. These constraints necessitated an expedited Guidance, Navigation, and Control (GNC) development schedule, development began with a navigation sensor trade study using Linear Covariance (LinCov) analysis and a rapid sensor downselection process, resulting in the use of commercial off-the-shelf (COTS) sensors which could be procured quickly and subjected to in-house environmental testing to qualify them for flight. A neural network was used to enable a COTS camera to provide bearing measurements for visual navigation. The GNC flight software (FSW) algorithms utilized lean development practices and leveraged the Core Flight Software (CFS) architecture to rapidly develop the GNC system, tune the system parameters, and verify performance in simulation. This pace was anchored by several Hardware-Software Integration (HSI) milestones, which forced the Seeker GNC team to develop the interfaces both between hardware and software and between the GNC domains early in the project and to enable a timely delivery.

[View Full Paper]

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ADVANCED NAVIGATION APPLICATIONS AND TECHNOLOGIES

Session 7

National Chairpersons:

Renato Zanetti, The University of Texas Austin

Jay McMahon, University of Colorado Boulder

Local Chairpersons:

Ellis King, Lockheed Martin Space Systems Company

Lee Barker, Lockheed Martin Space Systems Company

Jeffrey Parker, Advanced Space

The following papers were not available for publication:

AAS 19-071 (Paper Withdrawn)

AAS 19-072 (Paper Withdrawn)

AAS 19-075 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 19-078 to -080

SIX DEGREE OF FREEDOM NAVIGATION USING ASTROPHYSICAL SIGNALS OF OPPORTUNITY

Joel T. Runnels* and Demoz Gebre-Egziabher†

In this paper, an estimator is derived for jointly estimating a spacecraft's position and orientation based on measurements of photons from astrophysical signals, specifically x-ray pulsars. It is shown that the accuracy of a navigation solution using x-ray pulsars is inherently coupled to the accuracy of the attitude solution. The efficacy of the estimator is demonstrated using Monte Carlo simulations which demonstrate the relationship between attitude solution error and position solution error. [View Full Paper]

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AAS 19-074

GOES-R SERIES GEO SIDE-LOBE CAPABLE GPSR POST-LAUNCH REFINEMENTS AND OPERATIONAL CAPABILITIES[*]

Graeme Ramsey,[†] Lee Barker,[‡] Jim Chapel,[‡] Stephen Winkler,[‡] Chuck Frey,[§] Douglas Freesland,[**] Perry Baltimore[††] and Alexander Krimchansky[‡‡]

This paper addresses three topics: 1) EOPP file modification, 2) Kalman filter parameter tuning regarding maneuvers and 3) off-pointing GPS tracking capability. GOES-R (Geostationary Operational Environmental Satellite-R Series) is the first in a 4-part series of new weather satellites set to replace and upgrade the older GOES constellation. Two GOES-R have been launched to date, GOES-S and GOES-R. GOES-R is operational over the Eastern United States and GOES-S over the West. The Global Positioning System Receiver (GPSR) on board this geostationary weather satellite is a mission critical enabling technology which has been both tested on the ground and evaluated on-orbit to verify its effectivity. Since becoming operational in November 2016, the GPSR onboard has performed extremely well under nominal circumstances. Further refinements regarding a variety of facets have taken place since the launch of GOES-R. One such refinement was the implementation of a modified EOP parameter set to improve ECEF to ECI transformation by restoring zonal tides removed from the EOP parameter fit per tech note 36. Another relevant refinement combined thermal consideration with Kalman filter tuning to improve orbit determination performance during maneuvers. Now with two years of data and two vehicles in orbit many capabilities of the GPSR have been identified and defined to a higher degree. For example, metrics on side-lobe tracking and off-Nadir tracking capabilities have been quantified to a high degree. This paper will seek to supplement the ESA GNC 2017 GOES-R GPSR performance paper as a deeper dive on specific tracking capabilities and performance improvements now implemented on the GOES-R and GOES-S vehicles. [View Full Paper]

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AAS 19-076

LIDAR-BASED AUTONOMOUS SHAPE RECONSTRUCTION AND NAVIGATION ABOUT SMALL BODIES UNDER UNCERTAINTY

Benjamin Bercovici[*] and Jay W. McMahon[†]

This paper proposes an integrated, autonomous framework dealing with the post-arrival shape reconstruction and proximity navigation about a small body, using Lidar point-clouds as the primary observation data. The proposed approach proceeds in three distinct phases: a point-cloud collection and registration phase, a shape reconstruction and fitting phase, followed by a navigation phase relying on the reconstructed shape model. The outputs of the three phases are as follows: a globally covering point-cloud of the shape of interest along with an initial orbit determination estimate of the spacecraft state, a reconstructed shape model augmented with an uncertainty model capturing shape fitting errors, and the spacecraft and small body Cartesian and rotational states. The presented framework avoids computational pitfalls customarily associated with optical navigation, and could open the door to more ambitious, autonomous small-body bound missions.

[View Full Paper]

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AAS 19-077

PROGRESSION OF RECOVERING TIME AND STATE FOR AUTONOMOUS NAVIGATION SYSTEMS IN DEEP SPACE

Andrew Dahir,[*] Daniel Kubitschek[†] and Scott Palo[‡]

As satellites become more abundant, the need for autonomous navigation becomes a greater necessity for deep space travel as communication resources become limited. When smallsats are in deep space, communication times between a satellite and the Earth can be prohibitive and ride-sharing opportunities as well as on-board faults can leave the smallsat without time information. The objective of this research is to investigate feasibility and develop the algorithms plus the concept of operations required to demonstrate autonomous cold-start determination of time and state for cis-Lunar and interplanetary missions utilizing an autonomous optical navigation system. Being able to quickly and autonomously recover time and position from an environment with no Earth contact will help deliver mission success and advance technologies for smallsats from current large satellite methods which require an Earth contact. Baseline hardware for a solution approach focuses on small satellite commercial-off-the-shelf which could then be used for larger missions. The impact of this concept crosses both human (full loss of communication scenario) and robotic (autonomous recovery from on-board fault) exploration applications, where some form of spacecraft-to-ground communication is required to establish approximates for time and position. In both cases, the current state-of-the-art navigation systems require some knowledge of time and some approximate position to initialize the estimation process before the mission objectives can be obtained. This approach uses optical observations of Jupiter to initially recover the approximate time and state. These observations are then followed by precise, filter-based determination of time, position and velocity from the chosen optical beacons available in interplanetary spaceflight. The innovation of this approach is to use Jupiter and the four Galilean moons periodicity to initially determine time. This capability is analogous to that of advanced star trackers that can initialize themselves by identifying any star field in the celestial sphere. This presentation will focus on advances from last year's paper. While the solution is applicable to a wide range of missions, this presentation will focus on small satellites used for solar system exploration using off-the-shelf hardware. By constraining the problem to off-the-shelf hardware, the solution will be directly applicable to any spacecraft for interplanetary missions. [View Full Paper]

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ADVANCED PROPULSION

Session 8

National Chairperson:

Jeff Sheehy, NASA STMD

Local Chairpersons:

John Abrams, Analytical Mechanics Associates, Inc.

Nick Patzer, Laboratory for Atmospheric and Space Physics (LASP)

The following paper was not available for publication:

AAS 19-086 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 19-088 to -090

AAS 19-081

PROPULSION-ENABLED, ESPA-CLASS SPACECRAFT FOR NEAR-EARTH APPLICATIONS

William D. Deininger,[*] Karen McConnell,[†] Paul Woznick,[‡] Reuben Rohrschneider,[§] Aaron Cross,[**] Suzan Green,[††] Amanda Grubb[‡‡] and Scott Mitchell[§§]

Ball Aerospace has been conducting detailed studies on the feasibility of accommodating chemical (including green) propulsion and solar electric propulsion (SEP) on small Ball Configurable Platform (BCP), ESPA-class spacecraft. The BCP-Small spacecraft bus is used as the baseline to leverage its flight heritage (STPSat-2, STPSat-3, GPIM (in storage, awaiting launch) and IXPE (under development). The study approach is focused on aligning the BCP-Small design with multiple ongoing and upcoming small sat pursuits. Work is focusing on Demonstration-Class and Operational-Class spacecraft product development with reduced recurring engineering, volume production capability and equivalent or improved capabilities. Propulsion module options are considered for both BCP-Small products. Chemical systems providing up to 100's of m/s ΔV and SEP providing up to 1000's of m/s ΔV are being assessed. Chemical systems being assessed include hydrazine-based systems and green propellant systems based on the propellants AF-M315E and LMP-103S. SEP systems include several different plasma thruster systems including Hall and ion. This work is making use of the improved mass qualification limits for ESPA, the newly defined ESPA-Heavy and ESPA-Grande. Mission applications in various Earth orbits are the current focus for propulsion-enabled, BCP-Small spacecraft. The results of the ongoing work show BCP-Small spacecraft can be modified to accommodate meaningful chemical propulsion or SEP capability while meeting the mass and volume constraints for ESPA and/or ESPA-Grande. Mission options starting in both GTO and LEO are included in the assessments. This paper further summarizes the BCP-Small spacecraft design and capabilities, status of the heritage flight and in-development programs and describes how the BCP-Small is adapted to include chemical or SEP along with on-orbit control. [View Full Paper]

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ANALYZING MISSION OPPORTUNITIES FOR EARTH TO MARS ROUNDTRIP MISSIONS

Brian J. Guzek,[*] James F. Horton[†] and C. Russell Joyner II[‡]

NASA and industry are studying future human exploration missions to Mars that occur across multiple mission opportunities between 2030 to the late 2050's. Aerojet Rocketdyne (AR) has been analyzing ballistic transfers for Earth to Mars for roundtrip missions over an even grid of departure dates and transfer times during those opportunities. Aerojet Rocketdyne's efforts are an attempt to ensure the most optimum planetary alignment conditions were characterized in order to explore the performance capabilities for hybrid solar electric-chemical, chemical, and nuclear thermal propulsion. AR has been working with NASA on several approaches to Mars mission architectures that use various forms of the three propulsion systems. All three of these propulsion systems employ trajectories that are semi-ballistic or ballistic during the Earth departure, Mars arrival/departure, or Earth return arrival. A combination of the NASA Copernicus trajectory program and orbital mechanics calculations are used to determine the delta-velocity (delta-V) values that will be used in mission architecture trades[1].

Departure dates and transfer times are utilized as inputs into NASA's Copernicus trajectory design software suite and used to solve Lambert's boundary-value problem to find the optimal and non-optimal transfers between the two planets. The Copernicus Lambert solver gives four solutions. The solution with the least total delta-V is the objective for the analysis that has been performed over several 7-8 year planetary synodic alignments. Both conjunction and opposition class trajectories have been analyzed with Copernicus to develop a Mars mission data book going out to 2055.

This paper will discuss the results of preparing this mission data book in order to provide the needed information for analyzing the impact of propulsion system performance on Earth-Mars missions into the 2050's and beyond. Some trade study results based on using the methodology developed with the Earth-Mars mission data book are in the final section of the paper for a Nuclear Thermal Propulsion (NTP) system and Mars crew vehicle architecture. [View Full Paper]

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AAS 19-083

LUNAR LANDING AND SAMPLE RETURN FROM NEAR RECTILINEAR HALO ORBIT USING HIGH-POWERED SOLAR ELECTRIC PROPULSION

James F. Horton,[*] Timothy Kokan,[†] C. Russell Joyner,[‡] Dennis Morris[§] and Rodney Noble[**]

In December 2017 the current administration made a single sentence change to US Space Policy Directive-1 which has refocused the country's space explorations efforts on a "return of humans to the Moon for long-term exploration and utilization." With this mandate the National Aeronautics and Space Administration has centered its near-term development activities on a lunar orbiting space station known as the "Gateway". This way-station in deep-space will host astronauts and provide a platform for lunar science. The Gateway sits in a special type of Earth-Moon halo orbit known as a Near Rectilinear Halo Orbit (NRHO) with a proximity that allows for tele-robotics with craft on the surface. It is anticipated that after small commercial landers and payloads begin surface exploration in the early 2020's, government funded or developed mid-sized landers (500-1,000 kg payload) will provide sample return capability. After 2024, it is envisioned that even larger landers (5,000-6,000 kg payload) will be deployed to allow for human return to the surface of the Moon after a 50+ year absence. With reuse and affordability being key to enabling any long-term deep-space campaign, Aerojet Rocketdyne (AR) has studied the use of its highly efficient and high powered solar electric propulsion (SEP) technology to deliver payloads to low lunar orbit (LLO) from the Gateway to reduce the size and cost of lander systems that use traditional chemical propulsion (LOX/H_2, LOX/CH_4, or NTO/MMH). AR is currently working with NASA to develop xenon-fueled SEP systems that would be used in the Gateway's Power and Propulsion Element (PPE) to provide power, thrust, and station-keeping. This paper explores using a SEP tug based on AR's Gateway PPE design to deliver a lander and/or return a science sample from the lunar surface. This derivative PPE could then be refueled at the gateway and reused to support subsequent exploration activities. Trajectory sensitivities and trades with respect to NRHO departure orbits (i.e. 4:1 Earth Sidereal, 9:2 Lunar synodic), PPE power level, lander mass, and lander propellant choice are presented to provide estimates for two-way payload capability, xenon utilization, and transfer times to the lunar surface and back. [View Full Paper]

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PROPELLING INTERPLANETARY SPACECRAFT UTILIZING WATER-STEAM

Jorge Martinez* and Jekan Thangavelautham†

Beyond space exploration, there are plans afoot to identify pathways to enable a space economy, where human live and work in space. One critical question is what are the resources required to sustain a space economy? Water has been identified as a critical resource both to sustain human-life but also for use in propulsion, attitude-control, power, thermal and radiation protection systems. Water may be obtained off-world through In-Situ Resource Utilization (ISRU) in the course of human or robotic space exploration that replace materials that would otherwise be shipped from Earth." Water has been highlighted by many in the space community as a credible solution for affordable/sustainable exploration. Water can be extracted from the Moon, C-class Near Earth Objects (NE-Os), surface of Mars and Martian Moons Phobos and Deimos and from the sur-face of icy, rugged terrains of Ocean Worlds. However, use of water for propulsion faces some important technological barriers. A technique to use water as a propellant is to electrolyze it into hydrogen and oxygen that is then pulse-detonated. High-efficiency electrolysis requires use of platinum-catalyst based fuel cells. Even trace elements of sulfur and carbon monoxide found on planetary bodies can poison these cells making them unusable. In this work, we develop steam-based propulsion that avoids the technological barriers of electrolyzing impure water as propellant. Using a solar concentrator, heat is used to ex-tract the water which is then condensed as a liquid and stored. Steam is then formed using the solar thermal reflectors to concentrate the light into a nanoparticle-water mix. This solar thermal heating (STH) process converts 80 to 99% of the incoming light into heat. In theory, water can be heated to 1000 K to 3000K with a resulting Isp from 190s to 320s. This propulsion system can offer higher thrust than current electrical propulsion methods and represents a high delta-v solution for small spacecrafts. A further understanding of the concentration sys-tem, implications for GNC and the heat transfer process in the nanofluid is presented in this work. [View Full Paper]

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AAS 19-085

DEVELOPMENT PLAN FOR A FISSION AND FUSION POWERED PROPULSION SYSTEM TO REACH MARS IN 45 DAYS

Jason Cassibry,[*] Dale Thomas,[†] Richard Wood,[‡] Robert Frederick[§] and Saroj Kumar[**]

Using straight line trajectory estimates, a 45 day rendezvous with Mars requires a ~20 MW power supply, 250 N thrust, and an I_{sp} of ~5,000 s, assuming a specific power of 5 kW/kg. A deep space mission to 125 AU in 10 years requires a 500 kW reactor running continuously for 6 years, 1 N thrust, and an I_{sp} of 75,000 s. Fusion or fission/fusion hybrid propulsion can provide the specific power and very high specific impulse (I_{sp}) during heliocentric cruise to enable the mission transit time goals to be met. However, like NEP, it may not satisfy the high thrust needs for time efficient planetary departure and capture maneuvers. Therefore, a hybrid propulsion system employing bimodal fission modules and a fusion module is proposed and discussed. Some of the key challenges to developing critical technologies will be discussed in this paper, and multi-body trajectory analysis will be performed to indicate the performance requirements and capabilities of such a system. [View Full Paper]

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AAS 19-087

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

Justin Koo†

The Air Force Research Laboratory (AFRL) performs R&D for development and sustainment of advanced space propulsion technology for DoD applications. Core programs span a broad range of propulsion options including both chemical and electric propulsion technologies. This presentation will provide a brief survey of the four main space propulsion technology areas under investigation at AFRL. The Test/Flight demonstration area primarily supports legacy systems and enhances the transition/integration of existing propulsion technologies, including HETs, onto DoD spacecraft. The advanced chemical propulsion area is focused on the replacement of hydrazine in the DoD fleet with higher performance IL formulations. Finally, the electrospray and pulsed electromagnetic areas are investigating the practical performance potential for high efficiency electric propulsion technologies. [View Full Paper]

* Note: This paper is an update of an earlier review paper presented at this conference in Reference 1.

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AUTONOMOUS NAVIGATION IN THE EARTH-MOON SYSTEM

Session 9

National Chairpersons:

Joel Parker, NASA Goddard Space Flight Center

Ryan Whitley, NASA Johnson Space Center

Local Chairpersons:

Ellis King, Lockheed Martin Space Systems Company

Lee Barker, Lockheed Martin Space Systems Company

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AAS 19-091

GUIDANCE AND NAVIGATION DESIGN TRADES FOR THE LUNAR PALLET LANDER

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Naeem Ahmad, Jason Everett and Kyle Miller[‡]

This paper provides an overview of a series of design trades in support of the NASA Lunar Pallet Lander (LPL) project. The vehicle is being designed to enable a high mass landing capability on the Lunar surface with a high precision. In order to provide clear requirements definition and preliminary design, the Guidance and Navigation Teams are assessing areas such as algorithm development, sensor architectures, and system-level sensitivities. These trades are enabled by the detailed six degree of freedom analysis tools. This mature simulation with the capability for closed- and open-loop simulation modes allows for high fidelity modeling and understanding of the system under design. The results show the feasibility and performance of the current vehicle to meet high accuracy landing requirements. [View Full Paper]

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AAS 19-092

DEEP-SPACE AUTONOMOUS NAVIGATION FOR THE LUNAR ORBITAL PLATFORM-GATEWAY

Sagar A. Bhatt,[*] Stephen R. Steffes[†] and Gregg H. Barton[‡]

As NASA's planning for missions in cis-lunar space progresses, deep space autonomous navigation is one critical component that must mature alongside. Recent work has shown the benefits of various onboard navigation technologies for the upcoming Orion EM-1 and EM-3 missions. This paper studies navigation for the Lunar Orbital Platform-Gateway to meet NASA requirements. In particular, the Gateway flight system must operate autonomously for at least 3 weeks. The need to station-keep in the Near-Rectilinear Halo Orbit without communication with ground controllers suggests a key driving requirement on the orbit determination system to work without reliance on the Deep Space Network (DSN). Three autonomous navigation options are examined: lunar beacons, X-ray pulsar navigation, and optical navigation. Linear covariance analysis demonstrates that all three can achieve sufficient performance to keep station-keeping costs within budget. [View Full Paper]

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AAS 19-093

THE DEEP SPACE POSITIONING SYSTEM (DPS) – NAVIGATOR CONCEPT FOR THE LUNAR GATEWAY

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The DPS-Navigator concept is a self-contained autonomous navigation hardware and software system that provides spacecraft on-board navigation throughout the solar system. It answers the question "where am I?" like the Global Positioning System (GPS), but without the need for the satellite infrastructure. For the lunar Gateway, DPS-Navigator would observe lunar landmarks to determine position information and compute orbital maneuvers to maintain the Gateway orbit when the crew is not present or to reduce the crew's dependence on ground-based mission control. The optical-only design is small (25 x 12 x 12 cm) and lightweight, less than 5 kg. Power requirements are less than 12 W with self-contained processing. Data link requirements (infrequent for set-up, monitoring, and maintenance) are less than 50 MB per day. DPS-Navigator leverages prior flight demonstrations of autonomous navigation (DS-1, Deep Impact, Stardust) to provide a more general and robust on-board solution. DPS-Navigator provides precise lunar landmark measurements using narrow angle field of view (FOV) optics and precise pointing knowledge using wide angle FOV optics. A more robust configuration of the DPS-Navigator uses optical and radiometric sensing. For the lunar Gateway, the optical-only version would be sufficient given the abundance of optical targets in the form of lunar surface landmarks. On-board navigation performance results using lunar landmarks are presented in this paper and shown to provide an alternative to traditional deep space network Earth-based radiometric techniques; thus, freeing Earth tracking stations and ground personnel for other support. [View Full Paper]

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AAS 19-094

THE CISLUNAR AUTONOMOUS POSITIONING SYSTEM, CAPS

Jeffrey S. Parker, Jonathon Smith, Alec Forsman, Christopher Rabotin, Charles Cain and Bradley Cheetham*

The Cislunar Autonomous Positioning System, CAPS, is a nearly non-invasive solution that provides inertial, absolute navigation to each cooperating spacecraft/lander near the Moon in a peer-to-peer, autonomous fashion. Each spacecraft in the network carries a CAPS board – much like a GPS board – and uses CAPS protocols and schedules to periodically transmit and receive radiometric signals from other spacecraft in the network, i.e., ranging tones and/or Doppler; the signals are used as navigation observables to derive an inertial solution. CAPS is built off of the navigation technique known as LiAISON (Linked Autonomous Interplanetary Satellite Orbit Navigation). LiAISON has been studied since 2004 and has been proven successful as a means to harness an asymmetric gravity field to derive absolute position and velocity information about two or more satellites using only inter-satellite range and range-rate tracking data. By using only inter-spacecraft measurements, CAPS is able to generate on-board navigation solutions that are independent of Earth-based tracking stations (though can and certainly will use those signals as well). This allows highly contested ground-contact time to be prioritized for spacecraft commanding and data return. Spacecraft participating in CAPS form a network in cislunar space and on the surface of the Moon that becomes increasingly effective at inertial navigation as more gravitational asymmetry is expressed in their combined geometry. [View Full Paper]

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AAS 19-096

GPS BASED AUTONOMOUS NAVIGATION STUDY FOR THE LUNAR GATEWAY

Luke B. Winternitz,* William A. Bamford,† Anne C. Long‡ and Munther Hassouneh*

This paper describes and predicts the performance of a conceptual autonomous GPS-based navigation system for NASA's planned Lunar Gateway. The system is based on the flight-proven Magnetospheric Multiscale (MMS) GPS navigation system augmented with an Earth-pointed high-gain antenna and, optionally, an atomic clock. High-fidelity simulations, calibrated against MMS flight data and making use of GPS transmitter patterns from the GPS Antenna Characterization Experiment project, are developed to predict performance of the system in the Gateway Near-Rectilinear Halo Orbit. The results indicate that GPS can provide an autonomous, realtime navigation capability with comparable, or superior, performance to a ground-based Deep Space Network approach using eight hours of tracking data per day. [View Full Paper]

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AAS 19-097

PREDICTED PERFORMANCE OF AN X-RAY NAVIGATION SYSTEM FOR FUTURE DEEP SPACE AND LUNAR MISSIONS

Joel Getchius,[*] Anne Long,[†] Mitra Farahmand,[†] Luke Winternitz,[‡] Munther A. Hassouneh[‡] and Jason W. Mitchell[‡]

In November 2017, the NASA Goddard Space Flight Center Station Explorer for X-ray Timing and Navigation Technology experiment successfully demonstrated the feasibility of X-ray Pulsar Navigation (XNAV) as part of the Neutron Star Interior Composition Explorer mission, which is an X-ray Astrophysics Mission of Opportunity currently operating onboard the International Space Station. XNAV provides a GPS-like, absolute autonomous navigation and timing capability available anywhere in the Solar System and beyond. While the most significant benefits of XNAV are expected to come in support of very deep-space missions, the absolute autonomous navigation and timing capability also has utility for inner Solar System missions where increased autonomy or backup navigation and timing services are required, e.g., address loss of communication scenarios.

The NASA commitment to develop a Gateway to support exploration of the Moon and eventually Mars, as well as current and future robotic missions such as James Webb Space Telescope and New Horizons, certainly will tax the existing ground based infrastructure in terms of availability. Therefore, an extended look at the feasibility and potential performance of XNAV for comparable missions is warranted. In this paper, we briefly review the XNAV concept and present case studies of its utility and performance for a Gateway orbit, Sun-Earth libration orbit, and a deep space transit trajectory. [View Full Paper]

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AAS 19-098

PROBA-3 PRECISE ORBIT DETERMINATION BASED ON GNSS OBSERVATIONS

Werner Enderle,[*] Francesco Gini,[†] Erik Schönemann,[‡] Volker Mayer[§] and Michiel Otten[**]

ESA's PROBA-3 mission[1] will demonstrate high-precision formation-flying of a pair of satellites in a High Eccentric Orbit (HEO) with new developed in-orbit technologies. It is a solar coronagraph science experiment consisting of two spacecraft, where the telescope of the solar coronagraph is mounted on one spacecraft, while the other spacecraft is maneuvered to block the solar disk as seen from the coronagraph spacecraft. The launch of the spacecraft is expected in late 2020. The PROBA-3 spacecraft pair will fly divided between periods of accurate formation flying, when payload observations will be possible, and periods of free flight. Each spacecraft will be able to maneuver itself. The typical separation distance between the spacecraft will be about 150 m. As the second spacecraft carrying the occultation disk is maneuvered relative to the primary spacecraft with the coronagraph on-board both spacecraft are considered to fly in the same orbit.

ESA's Navigation Support Office (NavSO), located at the European Space Operations Centre in Darmstadt, Germany will use this ESA mission to test, analyze and demonstrate advanced concepts for spacecraft precise orbit determination (POD). This paper will provide an overview of the expected performance for absolute- and relative satellite POD for the PROBA-3 mission, based on simulations conducted in the preparation for this mission. [View Full Paper]

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LESSONS LEARNED IN GUIDANCE, NAVIGATION AND CONTROL SIMULATION, VERIFICATION, AND VALIDATION

Session 10

National Chairpersons:

Mike Hughes, NASA Jet Propulsion Laboratory

Mike Moreau, NASA Goddard Space Flight Center

Local Chairpersons:

Dan Kubitschek, Laboratory for Atmospheric and Space Physics

Jim Chapel, Lockheed Martin Space Systems Company

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CONTACT DYNAMICS AT THE SPACE OPERATIONS SIMULATION CENTER

Alain Carrier,* Christopher Norman,† Neil Eshleman‡ and David Huish§

Lockheed Martin's Space Operations Simulation Center (SOSC) is a robotic hardware-in-the-loop testbed used for testing autonomous rendezvous, proximity operations, and docking (ARPOD) missions. A twelve meter tall robot is used to simulate spacecraft motion relative to a large selection of full-scale mockups including asteroids, other spacecraft, and an International Space Station (ISS) docking port. The robot has over 60 meters of motion and is accurate to better than a millimeter, which allows for the recreation of the most complex relative orbital dynamics. The SOSC has been used to successfully develop the software, sensors, and hardware to enable ARPOD for Orion, OSIRIS-REx, and other missions. Recently a force feedback system (FFS) was integrated into the SOSC robotic environment which makes full contact dynamic testing possible. The FFS accommodates a range of force/torque sensors such that a variety of contact missions can be simulated from satellite servicing to landing on asteroids. The software was developed to be flexible in order to simulate any spacecraft and gravity environment. By making the hardware and software of the FFS modular, the SOSC can accommodate any mission interested in contact dynamic testing. The SOSC has so far used the FFS to simulate landing on an asteroid in a micro-gravity environment, docking with the ISS in earth orbit, and the motion of a body in free space when acted on by an inertial fixed force. Unique lessons have been learned such as the nuances of selecting the proper force/torque sensors and how to compensate for Earth's gravity while simulating a micro-gravity environment. The FFS addition to the SOSC greatly advances the ability of the SOSC to test all phases of an ARPOD mission. [View Full Paper]

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AAS 19-103

SENSOR ANALYSIS, MODELING, AND TEST FOR ROBUST PROPULSION SYSTEM AUTONOMY

Jeb S. Orr*

An approach is presented supporting analysis, modeling, and test validation of operational flight instrumentation (OFI) that facilitates critical functions for the Space Launch System (SLS) main propulsion system (MPS). Certain types of OFI sensors were shown to exhibit highly nonlinear and non-gaussian noise characteristics during acceptance testing, motivating the development of advanced modeling and simulation (M&S) capability to support algorithm verification and flight certification. Hardware model and algorithm simulation fidelity was informed by a risk scoring metric; redesign of high-risk algorithms using test-validated sensor models significantly improved their expected performance as evaluated using Monte Carlo acceptance sampling methods. Autonomous functions include closed-loop ullage pressure regulation, pressurant leak detection, and fault isolation for automated safing and crew caution and warning (C&W). [View Full Paper]

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AAS 19-104

ADAPTATIONS OF GUIDANCE, NAVIGATION, AND CONTROL VERIFICATION AND VALIDATION PHILOSOPHIES FOR SMALL SPACECRAFT

Christopher M. Pong,[*] David C. Sternberg[†] and George T. Chen[‡]

Decades of experience developing increasingly capable and more complex spacecraft have resulted in a set of accepted practices and philosophies to verify and validate (V&V) guidance, navigation, and control (GN&C) subsystems. Until recently, small, low-cost spacecraft have had very simple or non-existent GN&C subsystems requiring minimal or no subsystem testing. As the next generation of small spacecraft take on more challenging GN&C requirements, the GN&C community is struggling with how to scale the subsystem V&V effort to produce spacecraft approaching the reliability of flagship-class missions while staying within the reduced resources of a small satellite project. For this paper, we will examine five aspects of GN&C V&V (requirements definition, software testing and analysis, hardware component testing, integrated vehicle testing, and in-flight V&V) and compare the V&V campaign of a flagship-class mission (Mars 2020) to that of two recent, successful CubeSat missions: ASTERIA and MarCO. Experiences from the development of these CubeSats yield valuable lessons learned and guidelines for future small spacecraft designers. [View Full Paper]

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AAS 19-105

A FORMAL APPROACH TO VERIFICATION & VALIDATION OF GUIDANCE, NAVIGATION, AND CONTROL ALGORITHMS

Jason Crane,[*] Abraham Vinod,[†] Joseph Gleason,[‡] Meeko Oishi,[§] Jason Westphal[**] and Islam Hussein[††]

The traditional Monte Carlo based approaches to Verification & Validation (V&V) of Guidance Navigation and Control (GN&C) algorithms suffers from drawbacks, including typically requiring a significant amount of computational resources to guarantee a candidate algorithm's appropriateness. Formal approaches to V&V of GN&C algorithms can help address these issues as they are not based on simulation. Therefore, we are investigating and developing an innovative formal V&V algorithm for spacecraft GN&C, specifically in the determination of safety of maneuvers for satellite Remote Proximity Operations and Docking (RPOD). Formal V&V methods could provide rigorous and quantifiable assurances of safety for a given satellite maneuver without the need to perform extensive simulations, enhancing the autonomous decision-making capability of a spacecraft with limited computational resources. The research leverages a novel approach to the forward stochastic reachability analysis problem utilizing Fourier transforms. Initial results indicate quantifiable assurance of safety for a maneuvering satellite reach and reach-avoid problem can be achieved that match (sometimes conservatively) the Monte Carlo runs but use up to three or more orders of magnitude less computation resources. [View Full Paper]

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AAS 19-106

VERIFICATION AND VALIDATION TESTING FOR THE PARKER SOLAR PROBE GUIDANCE AND CONTROL SYSTEM

Robin M. Vaughan,[*] Daniel J. O'Shaughnessy[*] and John H. Wirzburger[†]

Parker Solar Probe was launched on a 7-year mission to explore the Sun in August 2018. A successful first orbit was preceded and enabled by a rigorous test campaign prior to launch. This paper discusses two of the main portions of that test program used to characterize and verify the performance of the spacecraft's guidance and control system. An extensive set of stand-alone simulations was designed to demonstrate compliance with performance requirements and explore system behavior in response to a large set of fault conditions. Another set of simulations was designed to fully exercise the flight software and demonstrate compliance with software requirements. The scenarios covered by these tests are described and procedures used to implement and review simulation results are discussed. Resources and schedule to complete test runs and document the test results are also given. [View Full Paper]

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AAS 19-107

GOES-R SPACECRAFT VERIFICATION AND VALIDATION COMPARED WITH FLIGHT RESULTS*

Jim Chapel,† Tim Bevacqua,† Devin Stancliffe,† Graeme Ramsey,† Tim Rood,‡ Doug Freesland,§ John Fiorello and Alexander Krimchansky††**

The Geostationary Operational Environmental Satellite, R-Series (GOES-R) represents a dramatic improvement in GEO weather observation capabilities over the previous generation.[1] To provide these new capabilities, GOES-R incorporates a number of new technologies flying for the first time. As with any new spacecraft design, extensive ground testing was performed to validate the vehicle performance. In this paper, we present several successes and several lessons-learned from the GOES-R verification and validation (V&V) efforts. Included are the Dynamic Interaction Test (DIT) results for jitter assessment, and comparison to flight results. Also included are the effects of thermally-induced alignment perturbations, along with post-launch mitigations. Finally, we discuss unexpected GOES-17 gyro performance, which caused a Safe Mode entry shortly after launch. V&V mitigations are presented, which will be used for the next two GOES-R vehicles.

[View Full Paper]

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AAS 19-108

TESTING OF THE LUNAR RECONNAISSANCE ORBITER ATTITUDE CONTROL SYSTEM RE-DESIGN WITHOUT A GYRO

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The Lunar Reconnaissance Orbiter (LRO) was launched in 2009 and, with its seven science instruments, has made numerous contributions to our understanding of the moon. LRO is in an elliptical, polar lunar orbit and nominally maintains a nadir orientation. There are frequent slews off nadir to observe various science targets. LRO attitude control system (ACS) has two star trackers and a gyro for attitude estimation in an extended Kalman filter (EKF) and four reaction wheels used in a proportional-integral-derivative (PID) controller. LRO is equipped with thrusters for orbit adjustments and momentum management. In early 2018, the gyro was powered off following a fairly rapid decline in the laser intensity on the X axis. Without the gyro, the EKF has been disabled. Attitude is provided by a single star tracker and a coarse rate estimate is computed by a back differencing of the star tracker quaternions. Slews have also been disabled. A new rate estimation approach makes use of a complementary filter, combining the quaternion differentiated rates and the integrated PID limited control torque (with reaction wheel drag and feedforward torque removed). The filtered rate estimate replaces the MIMU rate in the EKF, resulting in minimal flight software changes. The paper will cover the preparation and testing of the new gyroless algorithm, both in ground simulations and inflight.

[View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL SOFTWARE

Session 11

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AAS 19-111

HYPERSONIC COMMUNICATIONS BLACKOUT: HOW LASERCOM COULD BE THE SOLUTION

Rachel M. Golding*

Communication is essential to the United States mission in space. As technology must function in a hypersonic environment, such as for re-entry and hypersonic weapons, RF communications can become degraded due to the formation of a plasma sheath around the spacecraft. Many experiments have attempted to mitigate this problem in various ways. However, this study will aim to show that optical communications offers a better chance of communicating in a hypersonic environment by virtually eliminating attenuation. Another obstacle, background noise, can be overcome using a Fabry-Perot filter in the receiver. A model was created for transmission of optical signals through a plasma sheath, showing that there is almost no attenuation at optical frequencies. Furthermore, a fused silica receiver filter was tested and proved to have a narrow enough bandwidth to potentially overcome the background noise of the plasma. In fact, laser communications has potential for a high data rate during reentry and hypersonic flight. [View Full Paper]

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AAS 19-112

RVS3000-3D LIDAR-POSE ESTIMATION FOR SATELLITE SERVICING

Christoph Schmitt,[*] Sebastian Dochow,[†] Johannes Both,[‡] Bernd Linhart,[§] Michael Schwarz[**] and Michael Windmüller[††]

For future missions, like on-orbit servicing, space debris removal or planetary landing, a powerful 3D imaging LIDAR system is required. In addition, the application of advanced image processing techniques will be essential in order to safely operate a spacecraft relative to an uncooperative target object. Jena Optronik's new 3D LIDAR called RVS3000-3D represents a solution to both challenges via the combination of a high resolution scanning LIDAR with robust pose estimation algorithms. In the presentation we will review the properties of the RVS3000-3D and its ambitions to represent a one-box solution for space applications ranging from LEO ISS servicing to upcoming robotic activities in GEO. The RVS3000-3D LIDAR has been selected by Northrop Grumman In-novation Systems to serve as docking sensor for a 15 year GEO satellite servicing mission. The system has been fully qualified in 2018 and the first Flight Model was delivered in September 2018. The qualification included various measurement and test campaigns with an Engineering Model of the RVS3000-3D. We will summarize the main test results with special focus on the 3D imaging capabilities of the sensor and the performance of its pose estimation algorithms in real life experiments. [View Full Paper]

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EFFICIENT ON-ORBIT SINGULARITY-FREE GEOPOTENTIAL ESTIMATION

Joel Amert,* Evan Anzalone† and T. Emerson Oliver‡

For vehicles in orbital cruise, either in orbit around a body or in a transfer orbit, gravity is the primary external force; therefore, the complexity of the geopotential model heavily influences the accuracy of the navigation state. As this type of spacecraft requires a highly accurate geopotential model and performs the computation numerous times a second, this calculation needs to be efficient. This calculation needs to include the first and second derivatives of the geopotential because navigation systems can require both the gravitational acceleration and gradient for inertial integration and state filtering. The most efficient method for calculating the geopotential, the forward column method, is discussed in detail, as well as a method to avoid the singularities that exist when using this method. This is shown to decrease the computation time of the geopotential compared to other popular methods. In addition, methods for first and second order propagation are discussed, which decrease the rate at which the full geopotential model needs to be calculated while maintaining the accuracy required of navigation systems. These estimation methods are shown to decrease the necessary computation of the gravity model by multiple orders of magnitude. This method decreases the computation time of the Exploration Upper Stage navigation system geopotential model by potentially an order of magnitude compared with the previous model without affecting the navigation error. A properly implemented geopotential model can have the accuracy of an 8x8 model while approaching the computational requirement as using only the J234 coefficients. [View Full Paper]

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AAS 19-115

A METHOD TO ESTIMATE CO-STATES FROM A GIVEN NEAR OPTIMAL TRAJECTORY FOR LOW THRUST ORBIT TRANSFER

Santosh Ratan[*]

A new method is presented to estimate the initial guess of the co-states in the two-point boundary value problem which arises in the optimization of low thrust trajectory profile for orbit transfer. The proposed method uses a known thrust trajectory which may be approximately optimal. The original problem to find the initial co-states from the given thrust trajectory is non-linear and difficult to solve. The proposed approach reformulates this non-linear problem into a less accurate but linear problem, solution for which is easy. A numerical example is given to illustrate the method. [View Full Paper]

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AAS 19-116

IMAGING X-RAY POLARIMETRY EXPLORER DEPLOYMENT DYNAMICS DEVELOPMENT WITH SIMULATION SOFTWARE IMPLEMENTATION

Cody Allard,[*] Jeff Bladt[†] and Ian Gravseth[‡]

The Imaging X-ray Polarimetry Explorer (IXPE) spacecraft has a deployable boom section which involves a stowed rotated coil boom that translates and rotates the payload with respect to the bus during deployment. The spacecraft dynamics needs to be considered while developing concept of operations (ConOps) for deployment and to analyze the impact on the ADCS. This paper develops the equations of motion (EOMs) of the IXPE deployment dynamics while keeping the simulation software architecture in consideration. This is an important aspect because although this problem results in a unique phenomenon, the formulation should still be capable of being incorporated into a general software architecture for spacecraft dynamics. The dynamics are rearranged and placed into the form of the back-substitution method to be utilized in the software implementation. The paper also includes verification of the dynamics simulation by checking conservation of energy and momentum. [View Full Paper]

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ADVANCES IN GUIDANCE, NAVIGATION AND CONTROL HARDWARE

Session 12

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Local Chairpersons:

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AAS 19-121

MODELING AND OPTIMIZING A DEFORMABLE CARBON FIBER REINFORCED PLASTIC REFLECTOR USING FINITE ELEMENT ANALYSIS

Sean A. Sutedjo[*] and Tanaka Hiroaki[†]

Space situational awareness is becoming a priority in the militaries of both Japan and the United States; however, to accomplish this mission, communications need to be adaptable to the environment of space when components are damaged by debris or radiation. One way to do this is by making antennas deformable and adaptable. The purpose of this study is to model and optimize a carbon fiber reinforced plastic reflector using finite element analysis. To create high performance reflectors, surfaces need be deformable to correct for errors, and this is done by using actuators that control the surface shape of the reflector. By using finite element analysis, the reflector can be partitioned into elements and nodes. Finite element analysis allows the adjustment of these nodes and can predict how the rest of the surface will react due to a forced displacement by an actuator. In this study Abaqus and MatLab are used to make a finite element model of the reflector and to optimize the reflector. In this study Zernike polynomials are used as the target shape; because Zernike polynomials are known to be the most common deformations needed to fix path length errors in communications. This study looks at how the actuators should displace certain nodes to get the target shape, determined by the Zernike polynomial, and compare the actual deformation to the target deformation. The goal is to decrease this error by changing the layout of the composite layers and increasing the number of actuators. Carbon fiber reinforced plastic allows the reflector surface to be easily adjusted and controlled, but depending on the layout of the composite layers, error between the target and actual shape can vary. This study focuses on optimizing that layout by testing different angles of composite layers and seeing which ones give the least amount of error. Error can also be mitigated by increasing the number of actuators on the reflector. More actuators on the reflector simply allow for increased controllability, but also increase in cost. This study concludes that there is a family of composite layouts that mitigate error, but more research needs to be done to find a fully optimized reflector layout. Fully adaptable reflectors are in reach which could increase the performance of antennas dramatically; more studies on deformable reflectors should be encouraged especially to help increase the space situational awareness of the United States. [View Full Paper]

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AAS 19-122

AURIGA
A RELIABLE AND AFFORDABLE STAR TRACKER FOR CONSTELLATIONS AND SMALL SATELLITE MISSIONS

Benoit Gelin,[*] Pierre-Yves Bretécher, Laurent Nicollet and P-E. Martinez[†]

AURIGA is the new low-cost star tracker designed by Sodern dedicated to smallsat applications. In this paper, we will present the AURIGA-CP and AURIGA-SA versions and describe how these products respond to new-space requirements leveraging Sodern's extensive experience in star trackers. We also describe a wide range of testing solutions to support assembly, integration, and validation. Lastly, we describe our advanced production capabilities that employ disruptive screening practices, utilization of COTS parts, and simplified assembly and testing to reach a throughput of one optical head within two hours. [View Full Paper]

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AAS 19-123

ACTIVE MAGNETIC FIELD MITIGATION IN A REACTION WHEEL

Anja Nicolai,[*] Stephan Stoltz,[*] Olaf Hillenmaier,[†] Jonathan Ludwig,[†] Christian Strauch[†] and Dr. Sebastian Scheiding[*]

Many scientific satellite mission instruments rely on magnetic field measurements or are influenced by the satellite's magnetic dipole moment. Also, for attitude control, the magnetic dipole moment of the satellite causes disturbance torques when interacting with the Earth's magnetic field. Main contributors to the magnetic field of a satellite are the reaction wheels. Their internal design (electric motors, ferromagnetic parts) and high-speed operation, result in significant electromagnetic stray fields in various frequency ranges. To meet magnetic cleanliness requirements and to prevent high magnetic disturbance torques, reaction wheels are often housed in additional shielding on-board the satellite. This results in a significant mass increase and requires more magnetic (shielding) material on-board the satellite, which could in turn distort the magnetic field.

This paper describes the continuing efforts to achieve a magnetically clean reaction wheel. Mitigation techniques to minimize the magnetic field of the wheel are described, one of them being an active magnetic field compensation system counteracting the changing magnetic field emissions from the wheel. The motor emissions are measured for different operational modes and are modelled according to these measurements. The opposite field is then applied with the active compensation. The paper will discuss feasibility and challenges of the approach and conclude with recommendations for the next development phases. [View Full Paper]

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AAS 19-124

THE HADAMARD VARIANCE FOR RATE SENSING GYROSCOPE NOISE CHARACTERIZATION

Matthew Hilsenrath*

Gyroscope noise is commonly analyzed in the time domain utilizing the Allan Variance, reformulated to determine noise stability on a rate sensing gyroscope signal. This paper considers the Hadamard variance for this same purpose, and makes the case by applying both Allan Variance and Hadamard Variance analysis methods to simulated gyroscope rate data. The performance metrics are determined by coefficients of noise types which are found to be equivalent between the two characterization methods. [View Full Paper]

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THE KODIAK GNSS RECEIVER FOR MICROLAUNCHERS AND SOUNDING ROCKETS

Andreas Grillenberger,[*] Benjamin Braun[†] and Markus Markgraf[‡]

There have been significant changes to the number and variety of Global Navigation Satellite Systems in the past decade. While commercial manufacturers have quickly provided suitable solutions for the mass-market as well as high-budget space missions, there is still a gap in affordable receivers specialized for microlaunchers and sounding rockets. Based on GSOC's experience with the Phoenix GPS receiver, which has been successfully flown on numerous sounding rockets and LEO satellites in the past, the Kodiak GNSS receiver platform has been developed. With its modular design approach and source code access, the Kodiak receiver can be tailored to a specific mission while keeping the overall complexity of the system moderately low. The receiver uses a System-on-Chip FPGA with a dual-core ARM processor. Special care has been paid to ensure the exact synchronization of external Inertial Measurement Units (IMU) with the receiver time while the receiver interfaces also allow synchronization of other sensors, for example sun sensors. The paper provides a description of the Kodiak GNSS Receiver development and verification. It discusses the results of a flight experiment onboard a rocket and compares the Kodiak results with the performance of other flown on-board sensors. Conclusions of the experiment are drawn and the planned future work is discussed. [View Full Paper]

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AAS 19-126

AIRBUS DEFENCE AND SPACE CONTROL MOMENTUM GYRO NEW CMG FOR AGILE SATELLITE

Philippe Faucheux* and Anthony Pepoz†

The overall mission success drivers of the spacecraft pointing accuracy are a complex combination of multiple contributors, however, Control Moment Gyro (CMG) design choices and intrinsic performances are one of the major enablers for such a result. The CMG developed by Airbus Defence and Space offers to spacecraft users all required performances contributing to AOCS performances.

This paper describes the new and optimized CMG. This CMG 40-60 (providing an angular momentum of 40 Nms and an output torque of 60 Nm) integrates all improvements from previous development. This product results of more than 20 years experience of design, manufacturing and testing of CMG.

Finally, a specific section will describe the recently developed NEWTON package proposed by Airbus Defence and Space under CNES support (French Space Agency) to simplify use of CMG at spacecraft level. [View Full Paper]

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AAS 19-127

EXPLOITING TERRESTRIAL MEMS GYRO DEVELOPMENTS

Dick Durrant,* Mike Utton,† Eric Whitley‡ and Steeve Kowaltschek§

Thales Alenia Space UK Limited (TAS-UK) have been at the forefront of the migration of terrestrial MEMS technology to the space domain for over the last 10 years. This has resulted in the development of the MEMS Rate Sensor products SiREUS, SENTINEL-3 and MTG, and the Rover Vehicle Inertial Measurement Unit (RV-IMU) for ExoMars. The evolution of these developments towards next generation MEMS Gyro products is targeting both a significant reduction in recurring cost and an evolutionary improvement in performance over the next 5 years for telecom satellites, in particular within large constellations, with the products offering benefits to other space domains.

The next evolution of the Unit design is based on the development and qualification of a modular gyro unit that maximizes the potential of the latest Silicon Sensing MEMS detector that provides medium level performance, but in a reduced cost package. The initial phase of the development is based on qualifying an FPGA/discrete electronics Unit and the MEMS Gyro Detector in order to provide a flight capability from mid-2019. Further enhancements address the completion of the development and qualification of a radiation hardened mixed signal ASIC, which will provide significant cost-reduction opportunities for both standalone and constellation usage.

This paper presents the status of the on-going SiREUS NG10 Gyro development and the parallel detector qualification, as well the overall product development planning to place the technology in context. [View Full Paper]

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SPACE OBSERVATORY LINE-OF-SIGHT JITTER/MICRO-VIBRATION

Session 13

National Chairpersons:

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Local Chairpersons:

Mike Osborne, Lockheed Martin Space Systems Company

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A SURVEY OF THE SPACECRAFT LINE-OF-SIGHT JITTER PROBLEM

Cornelius Dennehy* and Oscar S. Alvarez-Salazar†

Predicting, managing, controlling, and testing spacecraft Line-of-Sight (LoS) jitter due to on-board internal disturbance sources is a challenging multi-disciplinary systems engineering problem, especially for those observatories hosting extremely sensitive optical sensor payloads with stringent requirements on allowable LoS jitter. Some specific spacecraft jitter engineering challenges will be introduced and described in this survey paper. Illustrative examples of missions where dynamic interactions have to be addressed to satisfy demanding payload instrument LoS jitter requirements will be provided. Some lessons learned and a set of recommended rules of thumb are also presented to provide guidance for analysts on where to initiate and how to approach a new spacecraft jitter design problem. These experience-based spacecraft jitter lessons learned and rules of thumb are provided in the hope they can be leveraged on new space system development projects to help overcome unfamiliarity with previously identified jitter technical pitfalls and challenges. [View Full Paper]

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GOES I-M: A RETROSPECTIVE LOOK AT IMAGE NAVIGATION AND REGISTRATION (INR), JITTER AND LESSONS LEARNED

John Sudey, Jr.,[*] Michael Hagopian[†] and Cornelius Dennehy[‡]

The Geostationary Operational Environmental Satellite (GOES) I-M series of spacecraft was the second generation of United States meteorological observational platforms in geosynchronous orbit. They served as the principal Earth-viewing observational platforms for continuously monitoring dynamic weather events from the mid-1990s and into the 21st century. This paper will look back at the program framing key system attributes of the mission, which necessitated a multi-layered development approach to meet stringent meteorological instrument Line-of-Sight (LoS) pointing and pointing stability requirements. The overall approach involved understanding, correcting, and avoiding pointing errors across a broad frequency range including what would typically be called dynamic interaction and jitter. Background information will be provided covering the mission architecture and program drivers. The systems solution for man-aging and mitigating the deleterious influences of on-board disturbances in order to meet the challenging instrument LoS pointing and jitter requirements will be described, along with the 'first of its kind' Image Navigation and Registration system. A broad look back at the lessons learned that emerged from the GOES I-M experience will be presented, with the intent of capturing general and specific insights for developers of future missions having stringent payload instrument pointing requirements. These discussions will touch on such critical aspects as defining jitter and related pointing requirements, the importance of early system architectural decisions, understanding and reducing on-board disturbances, the balance of test and analysis, and the imperative for maximizing on-orbit operational flexibility in order to accommodate unexpected dynamic interactions. [View Full Paper]

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IN-FLIGHT LINE-OF-SIGHT POINTING PERFORMANCE FOR THE GOES-16 AND GOES-17 SPACECRAFT*

Tim Bevacqua,† Jim Chapel,‡ Devin Stancliffe,§ Tim Rood, Doug Freesland†† and Alexander Krimchansky‡‡**

The Geostationary Operational Environmental Satellite-R program (GOES-R) has launched two of the next generation geostationary weather satellites, both of which are now fully operational. GOES-16 launched in November 2016, and GOES-17 launched in March 2017. In this paper, we present the pointing and pointing stability results of the two spacecraft, with specific focus on aspects of the design related to mitigating jitter. The flight instrument suite includes 6 seismic accelerometers sampled at ~2 KHz, allowing in-flight verification of pointing stability and comparison back to simulation predictions. This paper compares the observed flight results with the simulation predictions for acceleration and shock response spectrum (SRS) for various operational scenarios and instrument observation modes. Passive isolation of both the reaction wheels and the payload deck have proved to be effective in reducing jitter responses. Active Vibration Damping (AVD) of flexible-body modes attenuates the low frequency motion of the vehicle appendages, improving the low-frequency pointing performance. Knowledge of the instrument scan mirror motion is fed forward to the reaction wheel control, reducing disturbances on the spacecraft bus. Attitude knowledge and rate data are provided to the primary Earth-observing instrument with an accuracy defined by the Integrated Rate Error (IRE) requirements. The data are used to adjust instrument scanning. As we show in this paper, the in-flight performance of the GN&C design provides the necessary capabilities to achieve the demanding GOES-R mission objectives while its robustness enabled the simultaneous operation of the Advanced Baseline Imager (ABI) prime and redundant cryocoolers (CCs) to resolve an in-flight cooling anomaly on GOES-17.

[View Full Paper]

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AAS 19-134

TSIS EXPERIENCES WITH ISS JITTER FROM INCEPTION TO ON-ORBIT OPERATION

Patrick Brown and Andrew Engelmann*

The TSIS instrument has been measuring solar irradiance on a continual basis since January 2018 as an external payload on the ISS. In 2014 when TSIS was directed to fly on the ISS, the jitter environment was highly uncertain, so TSIS designed a robust gimbaled pointing system that showed excellent disturbance attenuation throughout the design, test, and on-orbit phases of the program. This paper discusses how TSIS accounted for this uncertain jitter environment throughout the life of the program.

TSIS was able to measure the ISS jitter during commissioning and determined that it was a relatively benign environment less than 4 arcseconds 1σ at low frequencies (<0.5 Hz). More importantly, the measured pointing performance of TSIS was consistently found to be 4 arcseconds 1σ, which easily satisfied the jitter requirement of 60 arcseconds 1σ. [View Full Paper]

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AAS 19-135

THE CONSEQUENCES OF YOUR MICROVIBRATION REQUIREMENT ON MECHANISMS DESIGN AND VERIFICATION - SOME DOS AND DON'TS

Geert Smet,[*] Jeroen Vandersteen[†] and Massimo Palomba[‡]

Microvibration is a multi-disciplinary problem, requiring inputs from specialists in several areas, such as Control, Structures, Mechanisms, Operations, Systems, etc. It is not always immediately obvious how decisions taken in our own field of specialty affect other subsystems. The requirement in exported microvibration for noise sources, typically mechanisms, is at least partially influenced directly by the Attitude Determination and Control System (ADCS). This paper aims to provide the reader with an idea of what is happening ‘over the fence’. It shows which difficulties a mechanisms engineer may encounter when trying to verify these requirements, and offers some insights in how to derive such a requirement in a way that satisfies the pointing performance, while not unnecessarily complicating the job of the mechanisms engineer. The paper starts by taking a critical look at a real exported microvibration requirement for the MetOp-SG Earth observation mission as derived in the very early stages of the project. As it turns out, this requirement is hard to verify for several reasons. The paper continues to outline a simplified approach on how a preliminary microvibration requirement can be derived using only the inputs available in the early phases of a project. This is then put in to practice for a MetOp-SG inspired case study. It is possible, with the benefit of hindsight, to derive a suitable requirement that at least partially alleviates verification issues at mechanism level. [View Full Paper]

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HIGH PRECISION POINTING CONTROL FOR WFIRST CGI INSTRUMENT*

Nanaz Fathpour,† Oscar Alvarez-Salazar,‡ David Arndt,‡ Milan Mandić,‡ Joel Shields,‡ Sam Sirlin‡ and Alfredo Valverde‡

Coronagraph Instrument (CGI) is one of two instruments on the Wide Field Infrared Survey Telescope (WFIRST), a NASA observatory, currently planned to launch in 2025. CGI is a JPL instrument and includes an imaging mode and a spectroscopic mode to perform exoplanet direct imaging and spectroscopic characterization of planets and debris disks around nearby stars. In order to achieve a very tight contrast stability, it requires pointing stability of 0.7 milliarcsecond (mas) RMS over the duration of the observation. This paper discusses CGI pointing architecture and approach to achieve this level of pointing performance, and flight implementation of the pointing system. The architecture is based on nested loops to reject Line Of Sight (LOS) jitter due to one of the largest disturbances on board, the reaction wheel assembly (RWA), as well as other disturbance sources, and thermal drift. The control architecture includes spacecraft ACS, as a feedback control that uses the low-order wavefront sensing (LOWFS) camera and Fast Steering Mirror (FSM) to suppress the telescope pointing drift and jitter, and a feedforward control, that is used to reject sinusoidal tones of the RWA. The LOWFS camera uses high flux from the obscured science target to achieve high sampling rate measurements of the LOS. The FSM has a local control loop that is used to linearize the piezoelectric actuators (PZT) hysteresis. Local feedback of the PZT displacement is provided by strain gauge sensors. This paper will present various aspects of the controller design, some sensor modeling, performance simulation, and operational constraints during CGI observations to meet tight pointing requirements. Some results from our Control Analysis Simulation Testbed (CAST) will be reported. [View Full Paper]

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FORMATION FLYING AND AUTONOMY

Session 14

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IMPROVED DATA COLLECTION USING MODEL PREDICTIVE CONTROL FOR CONSTELLATION POINTING

Reuben R. Rohrschneider,* Michael Lieber† and Carl Weimer‡

Science missions have traditionally been operated with the ground in the loop for all decisions, and little to no on-board autonomy. This restricts the ability to react to a dynamic scene or to capture some phenomena of interest, such as cloud dynamics, aggregation, and overshooting cloud tops – all of scientific interest. This paper proposes the use of the model predictive control (MPC) architecture to control a two-satellite constellation for measuring cloud aggregation in the tropics. The addition of MPC to control pointing improves data capture significantly over a nadir-staring system. The algorithms to control the system are run on a flight-like processor and execute at the required rate with margin.
[View Full Paper]

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AAS 19-142

USE OF LASER BEAMS TO CONFIGURE AND COMMAND SPACECRAFT SWARMS

**Himangshu Kalita,[*] Leonard Dean Vance,[†]
Vishnu Reddy[‡] and Jekan Thangavelautham[§]**

The availability of high-performance Commercial Off-The-Shelf (COTS) electronics that can withstand Low Earth Orbit conditions has opened avenue for wide deployment of CubeSats and small-satellites. Utilizing many scores, if not hundreds of these satellites can provide services to end-users on the ground such as position, navigation and tracking (PNT), persistent earth imaging, secure communications and off-grid data storage. Not all these satellites operate as intended in space and some may face premature failure and others may become immobile. This requires effective traffic management. In our approach, a secure laser beam will be used to directly communicate gestures and control one or more spacecraft, including a swarm. Each satellite will have a customized "smart skin" containing solar panels, power and control circuitry and an embedded secondary propulsion unit. A secondary propulsion unit may include electrospray propulsion, solar radiation pressure-based system, photonic laser thrusters and Lorentz force thrusters. Solar panels typically occupy the largest surface area on an earth orbiting satellite. Furthermore, our previous work has shown that commercial space-grade solar panels can be used to detect and distinguish blue and purple laser beams even when exposed to sunlight. A secure laser beam from another spacecraft or from the ground would interact with solar panels of the spacecraft. In a swarm, the secure laser beam would be used to first designate a temporary leader of the swarm, followed by configuration of the spacecraft swarm formation. In this paper we present a low-cost on-orbit mission concept to demonstrate the technology using a pair of 2U CubeSats and a dozen SunCube 1F FemtoSats. Using this low-cost mission, we hope to validate the technology in space. [View Full Paper]

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EFFECT OF NAVIGATION AND MANEUVER EXECUTION ERRORS ON OPTIMAL RPO TRAJECTORY DESIGN

Kai Jin,* Jianjun Luo† and David K. Geller‡

A robust trajectory optimization approach for rendezvous and proximity operations (RPO) in elliptical perturbed orbits with uncertainties is presented. The linearized dynamics are used to formulate a stochastic optimization problem that takes into account navigation errors, maneuver execution errors, and trajectory dispersion. A stochastic optimization problem is then defined based on a performance index equal to the sum of the expected maneuver delta-v and the 3-sigma delta-v dispersion, subject to a 3-sigma constraint on the final state dispersion. A genetic algorithm is used to solve the stochastic optimization problem, and a series of simulations are carried out to show that the stochastic optimal RPO trajectories can be significantly different than the corresponding deterministic optimal trajectories. [View Full Paper]

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SPACECRAFT SWARM ATTITUDE CONTROL FOR SMALL BODY SURFACE OBSERVATION

Ravi teja Nallapu[*] and Jekan Thangavelautham[†]

Understanding the physics of small bodies such as asteroids, comets, and planetary moons will help us understand the formation of the solar system, and also provide us with resources for a future space economy. Due to these reasons, missions to small bodies are actively being pursued. However, the surfaces of small bodies contain unpredictable and interesting features such as craters, dust, and granular matter, which need to be observed carefully before a lander mission is even considered. This presents the need for a surveillance spacecraft to observe the surface of small bodies where these features exist. While traditionally, the small body exploration has been performed by a large monolithic spacecraft, a group of small, low-cost spacecraft can enhance the observational value of the mission. Such a spacecraft swarm has the advantage of providing longer observation time and is also tolerant to single point failures. In order to optimize a spacecraft swarm mission design, we proposed the Integrated Design Engineering & Automation of Swarms (IDEAS) software which will serve as an end-to-end tool for theoretical swarm mission design. The current work will focus on developing the Automated Swarm Designer module of the IDEAS software by extending its capabilities for exploring surface features on small bodies while focusing on the attitude behaviors of the spacecraft in the swarm. We begin by classifying spacecraft swarms into 5 classes based on the level of coordination. In the current work, we design Class 2 swarms, whose spacecraft operate in a decentralized fashion but coordinate for communication. We demonstrate the Class 2 swarm in 2 different configurations, based on the roles of the participating spacecraft. The attitude behaviors of all the spacecraft are then converted to a line of sight (LoS) tracking problem with respect to different targets depending on their role in the swarm. A sliding mode control law is used to track the LoS with respect to assigned targets. Following this, we formulate the surface feature problem as an optimization problem which is solved using genetic algorithm optimization. Finally, the principles described are demonstrated by a numerical simulation of observing a simulated surface feature over the surface of asteroid 433 Eros. The results indicate successful performance of the design and control algorithms. [View Full Paper]

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AAS 19-146

PRECISE AND EFFICIENT FORMATION KEEPING AT EARTH-SUN L2 FOR STARSHADE MISSIONS*

Thibault L. B. Flinois,† Daniel P. Scharf,‡ Carl R. Seubert,† Michael Bottom§ and Stefan R. Martin‡

Current starshade concepts for imaging exo-Earths would operate at the Earth-Sun L2 point and consist of a starshade flying in formation tens to hundreds of thousands of kilometers from its telescope. The starshade would need to be aligned to the meter level across the line of sight from telescope to target star. This paper reports work aimed at maturing the technology readiness level of starshade formation sensing and control for the starshade science phase, during which precision alignment is required. First, the enabling formation fine lateral sensor using pupil-plane images and a formation control algorithm that provides high efficiency for science observations are presented. Then, other elements of an end-to-end starshade GNC system for the precision alignment phase are outlined: the longitudinal formation control algorithm, an RF communication link and ranging sensor, the formation estimator, and a thrust allocation algorithm. A high-fidelity simulation environment, which includes dynamics, actuator, and sensor models, is also summarized. Finally, for a representative observation scenario with WFIRST, this GNC system for precision alignment is demonstrated in a Monte Carlo simulation, robustly achieving observationally efficient meter-level control. [View Full Paper]

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RECENT EXPERIENCES IN GUIDANCE, NAVIGATION AND CONTROL

Session 15

National Chairpersons:

David Dannemiller, NASA Johnson Space Center

Sam Thurman, NASA Jet Propulsion Laboratory

Local Chairpersons:

Alex May, Lockheed Martin Space Systems Company

Drew Engelmann, Laboratory for Atmospheric and Space Physics

The following papers were not available for publication:

AAS 19-154 (Paper Withdrawn)

AAS 19-158 (Paper Withdrawn)

The following paper numbers were not assigned:

AAS 19-159 to -160

AAS 19-151

IN-FLIGHT VALIDATION OF THE OSIRIS-REX SAMPLE MASS MEASUREMENT TECHNIQUE*

Michael Skeen,† Huikang Ma,‡ E. B. Bierhaus,§ D. S. Lauretta**
and the OSIRIS-REx Team

The Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) spacecraft is the third NASA New Frontiers Program mission and arrived at the near-Earth asteroid (101955) Bennu in December 2018. After a thorough proximity operations phase to characterize the asteroid, the OSIRIS-REx spacecraft will fly a touch-and-go (TAG) trajectory to the asteroid's surface to collect at least 60 g of pristine regolith sample for Earth return. To verify the success of the TAG event, the spacecraft performs an in-flight measurement of the collected sample mass. This paper presents the in-flight validation and characterization of the Sample Mass Measurement (SMM) technique performed during the outbound cruise and approach phases of the mission. The OSIRIS-REx spacecraft performs several slew maneuvers to utilize an in-flight measurement of spacecraft inertia based on the principle of conservation of momentum. The resulting telemetry are processed to isolate the inertia contribution due to the collected regolith sample mass. Incremental exercises allowed characterization of smaller groupings of error sources prior to validating the full method. Results from the in-flight validation activities are presented along with improvements made to the technique to minimize sources of error. [View Full Paper]

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AAS 19-152

ECHOSTAR-III ATTITUDE RECOVERY

Xipu Li,* Santosh Ratan,† Frank Tsen‡ and Kuk Byun§

This paper describes the recovery techniques used to regain attitude control of a free spin geosynchronous satellite that lost attitude control due to an anomaly. The anomaly left the satellite dead, frozen and drifting in the active geo-synchronous orbit. Within three weeks, Lockheed Martin worked with EchoStar, the satellite's owner, to fully recover the spacecraft. Deorbit maneuvers were followed, and the satellite was successfully placed in the graveyard orbit[1]. This paper presents the spacecraft recovery process, emphasizing on the spacecraft attitude recovery. It includes the anomaly root cause analysis, spacecraft attitude determination approaches, and spacecraft attitude recovery execution.

[View Full Paper]

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AAS 19-153

VISION NAVIGATION USING THE ISS SELFIE

Fredy Monterroza,[*] Stephen R. Steffes,[†] Samuel M. Pedrotty,[‡] Shane B. Robinson[§] and Peter T. Spehar[**]

The ISS Selfie project was an on-orbit activity which used the ISS Mobile Servicing System (MSS) to “fly” a camera on a predefined trajectory in a variety of on-orbit lighting conditions to the International Docking Adapter 2 (IDA-2). The main purpose of the ISS Selfie activity was to obtain imagery and trajectory data of the last few meters of a spacecraft’s final approach to a docking system that meets the new International Docking System Standard (IDSS). Using this dataset, we evaluate a vision navigation algorithm, SAVANT, towards the purpose of vision-aided autonomous rendezvous and docking. SAVANT is a monocular vision only method that can leverage a priori known global information. The method uses ad hoc (opportunistic) features, globally known features and template matching features. Correspondences are established between 2D image locations and 3D inertial/absolute locations and a least squares minimization is solved to recover the pose. This optimization is done over a window of frames in a bundle adjustment, further refining poses and feature locations. The results of applying this method to the ISS Selfie data is presented. [View Full Paper]

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AAS 19-155

DEVELOPING THE GUIDANCE, NAVIGATION, AND CONTROL SYSTEM FOR NASA'S MARS HELICOPTER*

Håvard Fjær Grip†

As part of NASA's upcoming *Mars 2020* rover mission, a small-scale helicopter will be sent to Mars to conduct a series of demonstration flights, intended to validate the feasibility and utility of using helicopters for Mars exploration. The Mars Helicopter represents years of technology development, including a full Guidance, Navigation, and Control (GNC) system designed from the ground up. In this paper, we discuss the process of developing this system, from the initial concept, through early analysis and simulation, to testing, verification, and validation. [View Full Paper]

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AAS 19-156

SEEKER FREE-FLYING INSPECTOR GNC SYSTEM OVERVIEW

Samuel Pedrotty,[*] Jacob Sullivan,[†]
Elisabeth Gambone[‡] and Thomas Kirven[§]

Seeker is an ultra-low cost approach to highly automated extravehicular inspection of crewed or uncrewed spacecraft that has been designed and built in-house at the NASA Johnson Space Center (JSC). The first version of Seeker is intended to be an incremental development towards an advanced inspection capability. This effort builds on past free-flying inspector development efforts such as the Autonomous Extravehicular Activity Robotic Camera Sprint (AERCam Sprint) and Mini AERCam. Seeker was funded as an International Space Station (ISS) "X-by" Project, which required delivery of the vehicle approximately one year after authority to proceed and within the budget of $1.8 million. Seeker will fly onboard the NG-11 Cygnus mission in 2019 and will deploy after Cygnus' primary mission is completed. Seeker will perform inspection-like maneuvers within 50m of the target vehicle (Cygnus) and then dispose itself. The Seeker Guidance, Navigation, and Control (GNC) system is composed entirely of commercial off-the-shelf (COTS) and space-rated COTS items, an inertial-relative Multiplicative Extended Kalman Filter (MEKF), point-to-point guidance (with various additional modes such as stationkeeping), proportional-integral translational control, phase plane rotational control, and a state machine for automated mission moding with minimal ground input.

[View Full Paper]

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AAS 19-157

POINTING CONTROL OF A HIGH PERFORMANCE LARGE ANGLE SCAN MECHANISM

Yung Lee[*] and Miroslaw Ostaszewski[†]

Ball Aerospace is the developer of two optical Scan Mechanism Assemblies (SMAs), one for the Geostationary Environmental Monitoring Spectrometer (GEMS) and the other for the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instruments. These sensors will monitor pollution from geostationary orbit over a vast geographical area including the Contiguous Continental United States (CONUS) and parts of Canada and Mexico (greater North America), The South Korean Peninsula, Japan and the Asia Pacific and greater Asian Continent, and the European Continent.

This paper presents the mechanical design of the SMAs along with a systematic approach of the mechanism dynamic modeling, feedback control system design, plant characterization, and test results which verify the required performance of both SMAs. The current design achieves 46 μrad of pointing accuracy over ±3.1 degree FOR with a 100Hz closed-loop bandwidth and less than 0.4 μrad jitter.

Keywords: Scan mechanism assembly, two axis pointing mirror, jitter, feedback control

[View Full Paper]

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INDEX

NUMERICAL INDEX*

VOLUME 169 ADVANCES IN THE ASTRONAUTICAL SCIENCES, GUIDANCE, NAVIGATION AND CONTROL 2018 (2018)

(42nd AAS Rocky Mountain Guidance and Control Conference, January 31 to February 6, 2019, Breckenridge, Colorado, U.S.A.)

* Unless otherwise indicated all papers appear in Volume 169, *Advances in the Astronautical Sciences*.

AAS 19-061 Trajectory Characteristics of Spacecraft Propelled by a Ground-Based PLP System About a Non-Spherical Central Body, Ya-Ling Wen and Fu-Yuen Hsiao

AAS 19-062 Recent Flight Experiences of Blue Canyon Technologies Spacecraft, ADCS, and Components, B. Rogler, M. Baumgart, M. Ferenc, D. Sanders. This was the only poster paper presented at the conference, so it was placed in session 6. This was a presentation-only paper, and no written paper was available for publication.

AAS 19-063 Not Available (Withdrawn)

AAS 19-064 Sextant Navigation on the international Space Station: A Human Space Exploration Demo, Greg N. Holt and Brandon Wood

AAS 19-065 Rapid Development of the Seeker Free-Flying Inspector Guidance, Navigation, and Control System, Jacob Sullivan, Elisabeth Gambone, Thomas Kirven, Samuel Pedrotty and Brandon Wood

AAS 19-066 to -070 Not Assigned

AAS 19-071 Not Available (Withdrawn)

AAS 19-072 Not Available (Withdrawn)

AAS 19-073 Six Degree of Freedom Navigation Using Astrophysical Signals of Opportunity, Joel T. Runnels and Demoz Gebre-Egziabher

AAS 19-074 GOES-R Series GEO Side-Lobe Capable GPSR Post-Launch Refinements and Operational Capabilities, Graeme Ramsey, Lee Barker, Jim Chapel, Stephen Winkler, Chuck Frey, Douglas Freesland, Perry Baltimore and Alexander Krimchansky

AAS 19-075 Not Available (Withdrawn)

AAS 19-076 Lidar-Based Autonomous Shape Reconstruction and Navigation About Small Bodies Under Uncertainty, Benjamin Bercovici and Jay W. McMahon

AAS 19-077 Progression of Recovering Time and State for Autonomous Navigation Systems in Deep Space, Andrew Dahir, Daniel Kubitschek and Scott Palo

AAS 19-078 to -080 Not Assigned

AAS 19-081 Propulsion-Enabled, ESPA-Class Spacecraft for Near-Earth Applications, William D. Deininger, Karen McConnell, Paul Woznick, Reuben Rohrschneider, Aaron Cross, Suzan Green, Amanda Grubb and Scott Mitchell

AAS 19-082 Analyzing Mission Opportunities for Earth to Mars Roundtrip Missions, Brian J. Guzek, James F. Horton and C. Russell Joyner II

AAS 19-083 Lunar Landing and Sample Return from Near Rectilinear Halo Orbit Using High-Powered Solar Electric Propulsion, James F. Horton, Timothy Kokan, C. Russell Joyner, Dennis Morris and Rodney Noble

AAS 19-084 Propelling interplanetary Spacecraft Utilizing Water-Steam, Jorge Martinez and Jekan Thangavelautham

AAS 19-085 Development Plan for a Fission and Fusion Powered Propulsion System to Reach Mars in 45 Days, Jason Cassibry, Dale Thomas, Richard Wood, Robert Frederick and Saroj Kumar

AAS 19-086 Not Available (Withdrawn)

AAS 19-087 The Air Force Research Laboratory's in-Space Propulsion Program, Justin Koo

AAS 19-088 to -090 Not Assigned

AAS 19-138 to -140 Not Assigned

AAS 19-141 Improved Data Collection Using Model Predictive Control for Constellation Pointing, Reuben R. Rohrschneider, Michael Lieber and Carl Weimer

AAS 19-142 Use of Laser Beams to Configure and Command Spacecraft Swarms, Himangshu Kalita, Leonard Dean Vance, Vishnu Reddy and Jekan Thangavelautham

AAS 19-143 Effect of Navigation and Maneuver Execution Errors on Optimal RPO Trajectory Design, Kai Jin, Jianjun Luo and David K. Geller

AAS 19-144 Spacecraft Swarm Attitude Control for Small Body Surface Observation, Ravi Teja Nallapu and Jekan Thangavelautham

AAS 19-145 Not Available (Withdrawn)

AAS 19-146 Precise and Efficient Formation Keeping at Earth-Sun L2 for Starshade Missions, Thibault L. B. Flinois, Daniel P. Scharf, Carl R. Seubert, Michael Bottom and Stefan R. Martin

AAS 19-147 to -150 Not Assigned

AAS 19-151 In-Flight Validation of the OSIRIS-REx Sample Mass Measurement Technique, Michael Skeen, Huikang Ma, E. B. Bierhaus, D. S. Lauretta and the OSIRIS-REx Team

AAS 19-152 EchoStar-III Attitude Recovery, Xipu Li, Santosh Ratan, Frank Tsen and Kuk Byun

AAS 19-153 Vision Navigation Using the ISS Selfie, Fredy Monterroza, Stephen R. Steffes, Samuel M. Pedrotty, Shane B. Robinson and Peter T. Spehar

AAS 19-154 Not Available (Withdrawn)

AAS 19-155 Developing the Guidance, Navigation, and Control System for NASA's Mars Helicopter, Håvard Fjær Grip

AAS 19-156 Seeker Free-Flying inspector GNC System Overview, Samuel Pedrotty, Jacob Sullivan, Elisabeth Gambone and Thomas Kirven

AAS 19-157 Pointing Control of a High Performance Large Angle Scan Mechanism, Yung Lee and Miroslaw Ostaszewski

AAS 19-158 Not Available (Withdrawn)

AAS 19-159 to -160 Not Assigned

AUTHOR INDEX