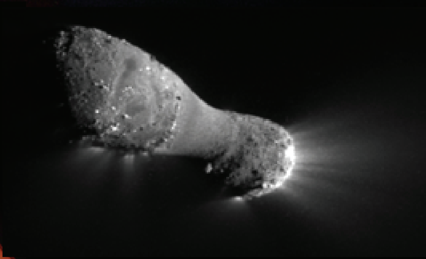
ASTRODYNAMICS 2011

Edited by
Hanspeter Schaub
Brian C. Gunter
Ryan P. Russell
William Todd Cerven

American Astronautical Society



Volume 142

ADVANCES IN THE ASTRONAUTICAL SCIENCES

ASTRODYNAMICS 2011

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Top photo: Cassini looking back at an eclipsed Saturn, Astronomy picture of the day 2006 October 16, credit CICLOPS, JPL, ESA, NASA;
Bottom left photo: Shuttle shadow in the sunset (in honor of the end of the Shuttle Era), Astronomy picture of the day 2010 February 16, credit: Expedition 22 Crew, NASA;
Bottom right photo: Comet Hartley 2 Flyby, Astronomy picture of the day 2010 November 5, Credit: NASA, JPL-Caltech, UMD, EPOXI Mission.

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FOREWORD

The 2011 Astrodynamics Conference was hosted by the American Astronautical Society (AAS) and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA). The conference was held July 31 – August 4, 2011, Girdwood, Alaska, U.S.A. There were some 220 papers presented in 28 technical sessions. Session topics included Asteroid & NEO; Orbital Debris; Dynamical Systems Theory; Special Topic: Autonomous Aerobraking; Trajectory Optimization; Formation Flying; Special Topic: Conjunction Assessment; Non-Earth Orbiting Missions; Orbit Estimation; Special Topic: ARTEMIS Mission; Planetary Mission Studies; Spacecraft GN&C; Satellite Constellations; Special Topic: MESSENGER at Mercury; Attitude D&C; Spacecraft Autonomy; Space Environment; Large Space Structures and Tethers; Optimal Control; and Rendezvous.

These astrodynamics conferences have been held annually since the mid-1960s, managed alternately by the American Astronautical Society and the American Institute of Aeronautics and Astronautics. Every second year the American Astronautical Society publishes the proceedings. The proceedings usually consist of a hard-copy volume or set of volumes plus a CD ROM (microfiche supplements in earlier years). This volume, *Astrodynamics 2011*, Volume 142, *Advances in the Astronautical Sciences*, consists of four parts totaling about 4,000 pages, plus a CD ROM which includes the papers in digital form. All of the available papers appear in full in Volume 142. A chronological index and an author index are appended to the fourth part of the volume. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume.

This volume is the latest in a sequence of Astrodynamics volumes which are published as a part of the American Astronautical Society series, *Advances in the Astronautical Sciences*. Several other sequences or subseries have been established in this series. Among them are: Space Flight Mechanics (annual), Guidance and Control (annual), International Space Conferences of Pacific-Basin Societies (ISCOPS, formerly PISSTA), and AAS Annual Conference proceedings. Proceedings volumes for earlier conferences are still available either in hard copy, CD ROM or in microfiche form. The appendix of the volume lists proceedings available through the American Astronautical Society.

In these proceedings volumes the technical accuracy and editorial quality are essentially the responsibility of the authors. The session chairs and the editors do not review all papers in detail; however, format and layout are improved when necessary by the editors.

We commend the general chairs, technical chairs, session chairs and the other participants for their role in making the conference such a success. A special word of thanks is also extended to those who assisted in organizational planning, registration and numerous other functions required for a successful conference.

The current proceedings are valuable in keeping specialists abreast of the state of the art; however, even older volumes contain some articles that have become classics and all volumes have archival value.

AAS/AIAA ASTRODYNAMICS VOLUMES

Astrodynamics 2011 appears as Volume 142, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Conference 2011.

Astrodynamics 2009, Volume 135, *Advances in the Astronautical Sciences*, Eds. A.V. Rao et al., 2892p, three parts plus a CD ROM Supplement.

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Spaceflight Mechanics 2011, Volume 140, *Advances in the Astronautical Sciences*, Eds. M.K. Jah et al., 2652p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2010, Volume 136, *Advances in the Astronautical Sciences*, Eds. D. Mortari et al., 2622p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2009, Volume 134, *Advances in the Astronautical Sciences*, Eds. A.M. Segerman et al., 2496p., three parts, plus a CD ROM supplement.

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Spaceflight Mechanics 2004, Volume 119, *Advances in the Astronautical Sciences*, Eds. S.L. Coffey et al., 3318p., three parts, plus a CD ROM supplement.

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Spaceflight Mechanics 2002, Volume 112, *Advances in the Astronautical Sciences*, Eds. K.T. Alfriend et al., 1570p, two parts.

Spaceflight Mechanics 2001, Volume 108, *Advances in the Astronautical Sciences*, Eds. L.A. D'Amario et al., 2174p, two parts.

Spaceflight Mechanics 2000, Volume 105, *Advances in the Astronautical Sciences*, Eds. C.A. Kluever et al., 1704p, two parts.

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Spaceflight Mechanics 1998, Volume 99, *Advances in the Astronautical Sciences*, Eds. J.W. Middour et al., 1638p, two parts; Microfiche Suppl., 2 papers (Vol. 78 *AAS Microfiche Series*).

Spaceflight Mechanics 1997, Volume 95, *Advances in the Astronautical Sciences*, Eds. K.C. Howell et al., 1178p, two parts.

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Spaceflight Mechanics 1994, Volume 87, *Advances in the Astronautical Sciences*, Eds. J.E. Cochran, Jr. et al., 1272p, two parts.

Spaceflight Mechanics 1993, Volume 82, *Advances in the Astronautical Sciences*, Eds. R.G. Melton et al., 1454p, two parts; Microfiche Suppl., 2 papers (Vol. 68 *AAS Microfiche Series*).

Spaceflight Mechanics 1992, Volume 79, *Advances in the Astronautical Sciences*, Eds. R.E. Diehl et al., 1312p, two parts; Microfiche Suppl., 11 papers (Vol. 65 *AAS Microfiche Series*).

Spaceflight Mechanics 1991, Volume 75, *Advances in the Astronautical Sciences*, Eds. J.K. Soldner et al., 1353p, two parts; Microfiche Suppl., 15 papers (Vol. 62 *AAS Microfiche Series*).

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Robert H. Jacobs,
Series Editor

PREFACE

The 2011 Astrodynamics Specialist Conference was held at The Hotel Alyeska in Girdwood, Alaska, from July 31 – August 4, 2011. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 270 people registered for the meeting; attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

There were 220 technical papers presented in 28 sessions on topics related to space-flight mechanics and astrodynamics. The 4 special sessions on Autonomous Aerobraking, Conjunction Assessment, the ARTEMIS Mission and MESSENGER at Mercury were well received and strongly attended.

The meeting included 4 social events. On Sunday the Early Bird Reception was held in the Kahiltna Court, on Monday evening there was a student social also in Kahiltna Court. On Tuesday evening the conference enjoyed a tram ride and dinner at the Glacier Express Restaurant, while on Wednesday evening the award ceremony and keynote address banquet was held in the Columbia conference rooms A/B/C. The keynote speaker was Dr. Robert D. Braun, the NASA Chief Technologist. The editors extend their gratitude to the Session Chairs who made this meeting successful: Ossama Abdelkhalik, Matthew Berry, Shyam Bhaskaran, Angela Bowes, Brent Buffington, Dennis Byrnes, David Dunham, Thomas Eller, David Folta, Ryan Frigm, Michael Gabor, Bob Glover, Yanping Guo, Felix Hoots, Alan Lovell, Don Mackison, James McAdams, Craig McLaughlin, Bo Naasz, Ryan Park, Chris Ranieri, Jon Sims, David Spencer, Thomas Starchville, Aaron Trask, Rao Vadali, Kenneth Williams, Roby Wilson, and Renato Zanetti. Our gratitude also goes to Tom Eller, Shannon Coffey, Felix Hoots, John Seago and James Kirkpatrick for their support and assistance.

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University of Colorado
AAS Technical Chair

Dr. Ryan P. Russell
Georgia Institute of Technology
AAS General Chair

Dr. Brian C. Gunter
Delft University of Technology
AIAA Technical Chair

Dr. William Todd Cerven
The Aerospace Corporation
AIAA General Chair

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SESSION 1: ASTEROID AND NEO I
Chair: Ryan Park, Jet Propulsion Laboratory

AAS 11 – 400

An Analysis of Multiple-Revolution Third Body Driven Plane Change Maneuvers

Eric Trumbauer and **Benjamin Villac**, Department of Mechanical and Aerospace Engineering, University of California, Irvine, California, U.S.A.

Third-body forces can greatly affect the orbital elements of spacecraft orbiting moons and small bodies. These forces can be harnessed to induce controlled orbital maneuvers such as plane changes. Previous studies have focused on a single revolution to effect these maneuvers. This paper extends this by considering multiple periapsis passages before recircularization. The performance envelope is evaluated and compared to previous studies. While the gains are modest in feasible cases, interesting structures emerge in relation to escape, capture, and libration point dynamics. These present opportunities for mapping nearby regions suitable for transfers to and from scientifically interesting near-polar orbits. [View Full Paper]

AAS 11 – 401
(Paper Withdrawn)

AAS 11 – 402

Application of Wide-Field Integration of Optic Flow to Proximity Operations and Landing for Space Exploration Missions

Michael A. Shoemaker and **Shinji Hokamoto**, Department of Aeronautics and Astronautics, Kyushu University, Nishi-ku, Fukuoka, Japan

New advances in vision-based navigation for micro air vehicles (MAVs) have been inspired by the biological systems of flying insects and the use of optic flow. These biologically-inspired optical sensor systems for MAVs are computationally efficient and have low mass and low power consumption, which makes them attractive for small spacecraft. This study explores the applicability of the wide-field integration (WFI) of optic flow to a spacecraft operating in close proximity to an asteroid. In contrast with past WFI work, this study uses an asteroid-relative reference trajectory and known *a priori* environment model such that the optimal sensitivity functions are recalculated onboard the vehicle at each time step. Numerical simulations with computer-generated images of the asteroid surface are used to estimate the vehicle's translational and angular velocities. Although the accuracy of these state estimates are reasonable considering the noise in the optic flow measurements, the onboard recalculation of the sensitivity functions for this time-varying scenario add computational burden which negates the main advantage of the WFI method. Hence, future applications to time-invariant scenarios for small-body missions are also discussed. [View Full Paper]

AAS 11 – 403

Comparison of Fragmentation/Dispersion Models for Asteroid Nuclear Disruption Mission Design

Brian D. Kaplinger and **Bong Wie**, Asteroid Deflection Research Center, Iowa State University, Ames, Iowa, U.S.A.

This paper considers the problem of developing statistical orbit predictions of near-Earth object (NEO) fragmentation for nuclear disruption mission design and analysis. The critical component of NEO fragmentation modeling is developed for a momentum-preserving hypervelocity impact of a spacecraft carrying nuclear payload. The results of the fragmentation process are compared to static models and results from complex hydrodynamic code simulations, developing benchmark initial conditions for orbital prediction algorithms. The problem is examined in a way that enables high-performance GPU acceleration of the resulting computational system, and the mission design fidelity is improved to allow for high throughput self-gravity and collision models of NEO fragments. Improvements to model efficiency are demonstrated using a range of orbits to assess disruption mission effectiveness. [View Full Paper]

AAS 11 – 404

Dynamics and Stability in a Triple Asteroid System: Applications to Mission Design

Julie Bellerose, Carnegie Mellon University Silicon Valley, NASA Ames Research Center, Moffett Field, California, U.S.A.; **Keaton J. Burns** and **Franck Marchis**, Carl Sagan Center at the SETI Institute, Mountain View, California, U.S.A.

We now count two triple asteroid systems in the NEA population. To enable exploration of such systems, we look at the dynamics of triple systems, starting from a two-body and a restricted three body dynamical models. The dynamics of an augmented system is inevitably rich, and we show spacecraft applications for rendezvous and proximity operations at these systems. Finally, we numerically investigate the perturbations and the stability within such systems to show and quantify fate of particles.
[View Full Paper]

AAS 11 – 405

Implementation of the NSTAR Thruster to Support Gravity-Tractor Operations

Dario O. Cersosimo, Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, Missouri U.S.A.

The NSTAR ion engine model, designed for the DS1 and Dawn missions, is implemented in a gravity-tractor spacecraft to support hovering operations. The model takes under consideration the operational limits of the thruster as well as the Isp profile for varying throttling levels. A gravity-tractor system was modeled and subject to operate under different guidance laws over a variety of asteroid configurations. Our results indicate the importance of an accurate propulsion system model for the gravity-tractor by showing that under certain scenarios, the propellant efficiency of the dynamic hovering laws is improved with respect to the classical inertial hovering. [View Full Paper]

AAS 11 – 406

Validation of a Finite Sphere Gravitation Model with Applications to Comet 67p/Churyumov-Gerasimenko

Paul V. Anderson and **Bogdan Udrea**, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.

Improved finite element methodology for estimating small body gravitational fields is validated through numeric analyses of asteroid Itokawa. The model implements uniform spherical elements of two sizes to obtain a fill ratio that approximates the asteroid shape model geometry to nearly 100% efficiency. The gravitational model is applied to the geometry of comet 67P/Churyumov- Gerasimenko and employed to analyze orbital dynamics and stability of ESA's *Rosetta* spacecraft during initial stages of the comet mapping and characterization phase in the comet environment. [View Full Paper]

AAS 11 – 407

(Paper Withdrawn)

AAS 11 – 408

Earth-Impact Probability Computation of Disrupted Asteroid Fragments Using GMAT/STK/Codes

Alan Pitz, **Christopher Teubert** and **Bong Wie**, Asteroid Deflection Research Center, Iowa State University, Ames, Iowa, U.S.A.

There is a nationally growing interest in the use of a high-energy nuclear disruption/fragmentation option for mitigating the most probable impact threat of near-Earth objects (NEOs) with a short warning time. Consequently, this paper investigates the orbital dispersion and impact probability computation problem of a disrupted/fragmented NEO using several computer programs, called General Mission Analysis Tool (GMAT) developed by NASA, AGI's Satellite Tool Kit (STK), and Jim Baer's Comet/asteroid Orbit Determination and Ephemeris Software (CODES). These tools allow precision orbital simulation studies of many fragmented bodies, with high-fidelity visualizations. Various mathematical models for impact probability computation are examined and compared to JPL's Sentry, which is a highly automated NEO collision monitoring system. For example, we obtained an impact probability of 4.2E-6 for asteroid Apophis on April 13, 2036, which is very close to 4.3E-6 predicted by JPL's Sentry system. Our research effort of exploiting various commercial software such as GMAT, STK, and CODES will result in a robust software system for assessing the consequence of a high-energy nuclear disruption mission for mitigating the impact threat of hazardous NEOs. [View Full Paper]

AAS 11 – 409

The Probability of Asteroid-Earth Collisions by Way of the Positional Uncertainty Ellipsoid

Christopher J. Polito and **David B. Spencer**, Department of Aerospace Engineering, The Pennsylvania State University, University Park, Pennsylvania, U.S.A.

An alternative to the conventional method for determining impact probability by an asteroid is presented that utilizes the positional uncertainty ellipsoid. This method is used commonly for Earth-orbiting satellite collision probability. In the scaling up process, the gravitational influence of one of the bodies in the collision is taken into account, namely that of the Earth. The restricted three-body problem is sufficient to provide a backdrop for the probability analysis, while making sure to note that the results are only hypothetical given a simplified dynamic model. Uncertainty is represented mathematically by the covariance matrix and is propagated into the future. Encounter regions are defined as regions along the nominal trajectory of the asteroid where the propagated uncertainty encloses the Earth. Probability is calculated by a triple integral of the probability density function (pdf) over the volume swept out by the Earth through the encounter region. The trend in probability calculated vs. initial uncertainty is investigated, and it is found that higher probabilities result from initial uncertainties that are tighter in the radial, in-track and out-of-plane directions. [View Full Paper]

SESSION 2: ORBITAL DEBRIS I

Chair: Dr. Thomas Starchville, The Aerospace Corporation

AAS 11 – 410

100-Year Low Earth Orbit Debris Population Model

Alan B. Jenkin, **Marlon E. Sorge**, **Glenn E. Peterson**, **John P. McVey** and **Bernard B. Yoo**, The Aerospace Corporation, El Segundo, California, U.S.A.

This paper presents a process to generate discrete future low Earth orbit debris populations for input to space system performance simulations. This process has several features that are different from previously developed debris prediction models, including use of the IMPACT breakup model and logarithmic down-sampling. Results show that the debris population caused by the current tracked population will grow even without future launches. Intact objects were ranked in terms of their potential to result in debris creation. Results preliminarily indicate that large numbers of collisions between large and small untracked objects may generate significant amounts of debris.
[View Full Paper]

AAS 11 – 411

Analyzing the Criteria for a Stable Environment

B. Bastida Virgili and **H. Krag**, ESA Space Debris Office, ESA/ESOC, Darmstadt, Germany

The number of human made objects in space has not stopped increasing since the beginning of spaceflight. Latest model predictions show that the population has already reached a point, where the number of objects would increase even without further human interaction. This also means that current mitigation measures are insufficient to stop this growth. In this study, with the help of an environment prediction model, we will investigate the drivers for the instability and propose solutions to achieve the stability based on a reformulation of the mitigation measures and on active removal missions. [View Full Paper]

AAS 11 – 412

Automated Ballistic Coefficient Estimation Technique to Analyze the Debris from the Cosmos-2251 and Iridium-33 Collision

John P. McVey and **Chia-Chun Chao**, Astrodynamics Department, The Aerospace Corporation, El Segundo, California, U.S.A.

The collision of the Cosmos-2251 and Iridium-33 satellites generated thousands of debris fragments. A ballistic coefficient estimation technique was developed to analyze these fragments and to extract information about the debris clouds for use in fragmentation models and other analyses. In order to characterize debris clouds, an automated estimation process was developed. The resulting ballistic coefficient estimate distributions from these debris clouds are distinctly different from each other and could yield information about the characteristics of the collision, which will aid in the determination of the characteristics of future collisions. [View Full Paper]

AAS 11 – 413

Determination of Orbit Cross-Tag Events and Maneuvers with Orbit Detective

Daniel L. Oltrogge and **Sal Alfano**, AGI's Center for Space Standards and Innovation, Colorado Springs, Colorado, U.S.A.

Track misassociation, cross-tag and orbit maneuver events can often be detected using a low-pass filter based upon pre- and post-event statistics accumulation. In this paper, we examine the implementation of such a filter in the Orbit Detective tool, and we apply the filter to the Galaxy 15 mission to determine cross-tag frequency of occurrence. Maneuver detection and calibration using such a low-pass filter are also discussed. [View Full Paper]

AAS 11 – 414

Effect of Future Space Debris on Mission Utility and Launch Accessibility

Glenn E. Peterson, Astrodynamics Department, The Aerospace Corporation, El Segundo, California, U.S.A.

Future growth of space debris in Low Earth Orbit will have an effect on two aspects of space operations: on-orbit mission utility and launch accessibility. Using a newly developed model, these two aspects are examined for three size regimes of debris: >10 cm (current tracking capability), 5-10 cm (upgraded tracking system), and 1-5 cm (potentially destructive to vehicle). Results show that as the debris environment grows, the number of actions (i.e., extra requests for tracking, maneuvers, etc.) at the examined orbit regime may be large enough to affect mission operations as will the potential amount of launch window closures. [View Full Paper]

AAS 11 – 415

Effects on Orbit Decay Due to CO_2 Growth in the Atmosphere

C. C. "George" Chao, **Bernard B. Yoo** and **Richard Walterscheid**, The Aerospace Corporation, El Segundo, California, U.S.A.

This paper presents the results of a study of the effects on orbit decay due to the gradual increase in carbon dioxide (CO_2) in the atmosphere. In this study, we assume three types of estimates of CO_2 growth: (1) simple linear growth of 1.7% per decade, (2) three-stage linear model by Walterscheid, and (3) composite model of 2.9% per decade for solar minimum and 0.8% per decade for solar maximum. Based on the above models for CO_2 growth, effects on orbit lifetime of LEO spacecraft were estimated using a semi-analytic orbit propagation tool, LIFETIME. Orbit lifetime can increase from 5% to as large as 67% depending on initial orbit altitude, ballistic coefficient and launch date. The Inter-Agency Space Debris Coordination Committee (IADC) requires that a LEO spacecraft must reserve adequate fuel to lower the perigee at end of life for natural reentry due to atmosphere drag decay within 25 years. Thus, the significantly increased orbit lifetime will result in increased fuel requirement for ensuring the natural decay time of an active LEO spacecraft within 25 years at end of life.
[View Full Paper]

AAS 11 – 416

Getting to Know Our Space Population from the Public Catalog

Daniel L. Oltrogge and **T. S. Kelso**, AGI's Center for Space Standards and Innovation, Colorado Springs, Colorado, U.S.A.

Our space population continues to increase as satellites are launched and debris-producing catastrophic events occur. For operators and policy makers, a periodic examination of the publicly available space population is useful. In this paper, bivariate distributions and visualizations of orbital elements and simple spatial density metrics clearly delineate regions of higher collision risk. For the highest risk region, benefits obtained by application of ISO orbital debris mitigation standards are discussed. Application of concentric spherical zone "Ring Shells" governed in latitude by object maximum latitude distribution helps provide a more realistic spatial density and collision probability picture compared with previous analyses. [View Full Paper]

AAS 11 – 417

Laser Tracking of Space Debris for Precision Orbit Determination

Craig Smith, **Yue Gao**, **Jizhang Sang** and **Ben Greene**, EOS Space Systems Pty Limited, Mt. Stromlo Observatory, Weston Creek, ACT, Australia

The relatively high levels of uncertainty in orbit predictions available from the current space surveillance and tracking systems has been established as the primary cause of the failure to predict (and avoid) the recent space crash between an active (Iridium) telecommunications satellite and a large debris object (a defunct Cosmos spacecraft). The most effective solution to this problem is by making significantly higher accuracy observations of satellite orbits.

Incorporating laser tracking systems into the existing network offers an alternative approach to radars that could potentially provide high-precision orbit updates for critical objects. EOS laser tracking systems use a short pulse laser range finder system and have already demonstrated the basic ability to track small space objects (< 10 cm diameter), and determine their location in space to within a few meters.

This paper describes the laser tracking systems and provide some results from the tracking demonstrations and precision orbit determinations. Also described are some upgrades that are currently being undertaken to extend the performance of the system and provide full automation of the tracking station operations. [View Full Paper]

AAS 11 – 418

Mitigating Potential Orbit Debris: The Deorbit of a Commercial Spacecraft

Timothy Craychee, Space Group, Applied Defense Solutions, Fulton, Maryland, U.S.A.; **Shannon Sturtevant**, Independent Senior Mission Analyst, Wheat Ridge, Colorado, U.S.A.

In the spring of 2011, a commercial spacecraft (SSC Object #27838) performed a final maneuver that sent the spacecraft into Earth's lower atmosphere resulting in a re-entry event that began over the southern Pacific Ocean. While it is not known if any spacecraft debris survived reentry, the design of the final orbit was such that potentially surviving debris would impact within a "safe zone" in the Pacific Ocean. The purpose of this paper is to report the deorbit trajectory design and implementation, which includes accommodating constraints and limitations of a vehicle whose design and mission never included a controlled deorbit. [View Full Paper]

AAS 11 – 419

Satellite Collision Probability Computation for Long Term Encounters

J. C. Dolado, CNES, Toulouse, France; **P. Legendre**, CEMAES, Fiac, France; **R. Garmier**, **B. Revelin**, CS-SI, Toulouse, France; **X. Pena**, CNES, Toulouse, France

With the significant increase in the number of satellite constellations and GEO objects, long-term encounters become common. Such geometries are characterized by a curvilinear relative motion and important position and velocity uncertainties. We first determine the relative velocity limits between the linear and non-linear encounters and the limits between negligible or not negligible velocity uncertainties. We then propose an algorithm combining a Monte Carlo and an importance sampling method to compute the collision probability for the curvilinear domain. We finally apply this algorithm to various encounters to demonstrate its efficiency in terms of accuracy and computation time. [View Full Paper]

SESSION 3: DYNAMICAL SYSTEMS THEORY
Chair: Jon Sims, Jet Propulsion Laboratory

AAS 11 – 420
A New Look at the Planar Dynamics of Libration-Orbit Coupling for Spacecraft

Jay W. McMahon and **Daniel J. Scheeres**, Aerospace Engineering Sciences, University of Colorado at Boulder, Colorado, U.S.A.

In this paper, the planar dynamics of libration-orbit coupling for a spacecraft in orbit about a spherical Earth are examined. The coupled equations, up to second order moments of inertia of the satellite, are derived from first principles. The integrals of motion available in the system are used to reduce the system to a 2 degree-of-freedom relative representation in the radial distance and libration angle of the spacecraft. The conservation of energy is used to derive zero-velocity curves which can be used to bound the libration angles of the spacecraft. Analytical relationships for the maximum libration amplitude based on initial conditions at a zero libration angle are derived. The usage of these analytical relationships are illustrated through simulation of the Space Shuttle in low-Earth orbit. Importantly, the analytical relationships are shown to be able to predict the eccentricity where the libration can be circulate. [View Full Paper]

AAS 11 – 421
Applications of Trajectories in the Vicinity of Sun-Earth L_3 for a Solar Observation Mission

Jonathan F. C. Herman and **Ron Noomen**, Delft University of Technology, The Netherlands; **Kathryn E. Davis** and **George H. Born**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.

This research investigates the feasibility of the L_3 region of the Sun-Earth system as the target for a solar observation mission that aims to observe the far side of the Sun as well as the higher (possibly polar) latitudes of the Sun. A grid search of the L_3 region is performed to locate families of periodic orbits, and the most promising results are identified. The possibility of using three-body dynamics for a transfer trajectory is briefly considered. Furthermore, the applicability of three-body dynamics for this region is discussed as well as the importance of other perturbations known to be present. Keeping the nature of the actual dynamics of this region in mind, the most interesting feasible orbits for a solar observation mission are identified. [View Full Paper]

AAS 11 – 422
(Paper Withdrawn)

AAS 11 – 423

Comparison of Low-Energy Lunar Transfer Trajectories to Invariant Manifolds

Rodney L. Anderson and **Jeffrey S. Parker**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

In this study, transfer trajectories from the Earth to the Moon that encounter the Moon at various flight path angles are examined, and lunar approach trajectories are compared to the invariant manifolds of selected unstable orbits in the circular restricted three-body problem. Previous work focused on lunar impact and landing trajectories encountering the Moon normal to the surface, and this research extends the problem with different flight path angles in three dimensions. The lunar landing geometry for a range of Jacobi constants are computed, and approaches to the Moon via invariant manifolds from unstable orbits are analyzed for different energy levels. [View Full Paper]

AAS 11 – 424

Estimation Strategies for Dynamical Systems with Equality Constraints

Julie J. Parish and **John E. Hurtado**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

Constrained dynamical systems are common in spacecraft and aerospace robotics. For the class of systems subject to equality constraints, monitoring constraint violation is useful for determining the more appropriate dynamical model of the system. In this paper, two strategies for sequentially estimating the states and constraint are presented with examples. The first method constructs the constraint estimate and variance from the linearized constraint relationship and state estimates, whereas the second method directly estimates both the constraint and variance. The constraint variance is then used to calculate uncertainty bounds for determining constraint violation and subsequently selecting the appropriate system model. [View Full Paper]

AAS 11 – 425

Flybys in the Planar, Circular, Restricted, Three-Body Problem

Stefano Campagnola, Outer Planet Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.;
Paul Skerritt, Physics Department, California Institute of Technology, Pasadena, California, U.S.A.;
Ryan P. Russell, Guggenheim School of Engineering, Atlanta, Georgia, U.S.A.

This paper presents an analysis of gravity assisted flybys in the planar, circular, restricted three-body problem that is inspired by the Keplerian map and by the Tisserand-Poincaré graph. The Flyby map is defined and used to give new insight on the flyby dynamics and on the accuracy of the linked-conics model. The first main result of this work is using the Flyby map to extend the functionality of the Tisserand graph to low energies beyond the validity of linked conics. Two families of flybys are identified: Type I (direct) flybys and Type II (retrograde) flybys. The second main result of this work is showing that Type I flybys exist at all energies and are more efficient than Type II flybys, when both exist. The third main result of this work is an example trajectory that consists of Type I flybys only, all outside the linked-conics domain of applicability. The trajectory is computed with the patched-cr3bp, and connects an initial orbit around Jupiter intersecting the Callisto orbit, to a 200-km circular orbit around Europa. The trajectory saves up to 30% in Δv (endgame and orbit insertion) compared to the current baseline for Europa orbiters computed in patched conics, without any significant increase to the time of flight nor the radiation dose.
[View Full Paper]

AAS 11 – 426

Identification of Input-Output Maps for Bilinear Discrete-Time State-Space Models

Haris Čelik, Royal Institute of Technology, Stockholm, Sweden; **Minh Q. Phan**, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, U.S.A.

This paper presents a formulation to identify the input-output maps of discrete-time bilinear state-space models. The new method uses input-output data from one experiment, and the input data need not be of special types such as extended pulses. The initial conditions can be non-zero and unknown. Recent methods, on the other hand, require data from multiple experiments, specialized input signals, and zero initial conditions. In the present method, a Nonlinear Auto-Regressive model with eXogenous input (NARX) is identified and used to predict the bilinear system response directly without returning to the bilinear state-space format. Numerical examples are provided to illustrate the identification method. [View Full Paper]

AAS 11 – 427

Multi-Body Capture to Low-Altitude Circular Orbits at Europa

Daniel J. Grebow, **Anastassios E. Petropoulos** and **Paul A. Finlayson**, Outer Planet Mission Analysis, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

For capture to a 200-km circular orbit around Europa, millions of different starting points on the orbit are propagated in the Jupiter-Europa Restricted 3-Body Problem. The transfers exist as members of families of trajectories, where certain families consistently outperform the others. The trajectories are not sensitive to changes in inclination for the final circular orbit. The top-performing trajectories appear to follow the invariant manifolds of L_2 Lyapunov orbits for capture into a retrograde orbit, and in some cases save up to 40% of the Δv from the patched 2-body problem. Transfers are attached to the current nominal mission for NASA's Jupiter-Europa Orbiter, where the total cost is roughly 100 m/s less than the baseline mission. [View Full Paper]

AAS 11 – 428

Poincaré Maps and Resonant Orbits in the Circular Restricted Three-Body Problem

Mar Vaquero and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

The application of dynamical systems techniques to mission design has demonstrated that employing invariant manifolds and resonant flybys enables previously unknown trajectory options and potentially reduces the ΔV requirements. An analysis of planar resonant orbits, as well as the computation and visualization of the associated invariant manifolds is explored in this analysis. Poincaré maps are an effective tool in the search for unstable resonant orbits and potential resonant transitions. Connections between the invariant manifolds associated with two-dimensional unstable resonant orbits for different energy levels are identified in the Saturn-Titan system and resonant periodic homoclinic-type connections are also summarized. As an application of this design process, the accessibility of Hyperion from orbits resonant with Titan is explored. [View Full Paper]

AAS 11 – 429

(Paper Withdrawn)

SESSION 4: SPECIAL TOPIC: AUTONOMOUS AEROBRAKING
Chair: Angela Bowes, NASA Langley Research Center

AAS 11 – 470
(See Session 6)

AAS 11 – 471
Autonomous Aerobraking Algorithm Testing in a Flight Software Simulation Environment

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Aerobraking has been successfully used to lower the propulsive ΔV required to achieve a desired science orbit for a number of missions, but it requires significant resources for tracking, navigation, modeling and maneuver planning. NASA is now exploring the transition of the technology to a spacecraft environment to enable autonomous aerobraking. This paper describes the modifications to flight and testbed software from a prior interplanetary mission that were made to incorporate aerobraking and navigation algorithms. The flight architecture and algorithms are presented along with preliminary simulation results for several typical orbits around Mars. [View Full Paper]

AAS 11 – 472
(Paper Withdrawn)

AAS 11 – 473
Autonomous Aerobraking: A Design, Development, and Feasibility Study

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Aerobraking has been used four times to decrease the apoapsis of a spacecraft in a captured orbit around a planetary body with a significant atmosphere utilizing atmospheric drag to decelerate the spacecraft. While aerobraking requires minimum fuel, the long time required for aerobraking requires both a large operations staff, and large Deep Space Network resources. A study to automate aerobraking has been sponsored by the NASA Engineering and Safety Center to determine initial feasibility of equipping a spacecraft with the onboard capability for autonomous aerobraking, thus saving millions of dollars incurred by a large aerobraking operations workforce and continuous DSN coverage. This paper describes the need for autonomous aerobraking, the development of the Autonomous Aerobraking Development Software that includes an ephemeris estimator, an atmospheric density estimator, and maneuver calculation, and the plan forward for continuation of this study. [View Full Paper]

AAS 11 – 474

Autonomous Aerobraking: Thermal Analysis and Response Surface Development

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A high-fidelity thermal model of the Mars Reconnaissance Orbiter was developed for use in an autonomous aerobraking simulation study. Response surface equations were derived from the high-fidelity thermal model and integrated into the autonomous aerobraking simulation software. The high-fidelity thermal model was developed using the Thermal Desktop software and used in all phases of the analysis. The use of Thermal Desktop exclusively, represented a change from previously developed aerobraking thermal analysis methodologies. Comparisons were made between the Thermal Desktop solutions and those developed for the previous aerobraking thermal analyses performed on the Mars Reconnaissance Orbiter during aerobraking operations. A variable sensitivity screening study was performed to reduce the number of variables carried in the response surface equations. Thermal analysis and response surface equation development were performed for autonomous aerobraking missions at Mars and Venus.

[View Full Paper]

AAS 11 – 475

(See Session 24)

AAS 11 – 476

Implementation and Simulation Results Using Autonomous Aerobraking Development Software

Robert W. Maddock, **Alicia Dwyer Cianciolo**, **Angela Bowes**, **Jill L. H. Prince**; NASA Langley Research Center, Engineering Directorate, Hampton, Virginia, U.S.A.; **Richard W. Powell**, Analytical Mechanics Associates, Hampton, Virginia, U.S.A.

An autonomous aerobraking software system is currently under development with support from the NASA Engineering and Safety Center (NESC) that would move typically ground-based aerobraking operations functions to onboard a spacecraft, reducing mission risk and cost. The software suite that will enable autonomous aerobraking is the Autonomous Aerobraking Development Software (AADS) and consists of an ephemeris model, onboard atmosphere estimator, temperature and loads prediction, and a maneuver calculation. The software calculates the maneuver time, magnitude and direction commands to maintain the spacecraft periapsis parameters within the desired design structural load and/or thermal constraints. The AADS is currently tested in simulations at Mars, with plans to also evaluate feasibility and performance at Venus and Titan.

[View Full Paper]

AAS 11 – 477

Onboard Atmospheric Modeling and Prediction for Autonomous Aerobraking Missions

Robert H. Tolson, Samuel P. Langley Distinguished Professor, NCSU, Hampton, Virginia, U.S.A.; **Jill L. H. Prince**, Atmospheric Flight and Entry Systems Branch, NASA Langley Research Center, Hampton, Virginia, U.S.A.

Aerobraking has proven to be an effective means of increasing the science payload for planetary orbiting missions and/or for enabling the use of less expensive launch vehicles. Though aerobraking has numerous benefits, large operations cost have been required to maintain the aerobraking time line without violating aerodynamic heating or other constraints. Two operations functions have been performed on an orbit by orbit basis to estimate atmospheric properties relevant to aerobraking. The Navigation team typically solves for an atmospheric density scale factor using DSN tracking data and the atmospheric modeling team uses telemetric accelerometer data to recover atmospheric density profiles. After some effort, decisions are made about the need for orbit trim maneuvers to adjust periapsis altitude to stay within the aerobraking corridor. Autonomous aerobraking would reduce the need for many ground based tasks. To be successful, atmospheric modeling must be performed on the vehicle in near real time. This paper discusses the issues associated with estimating the planetary atmosphere onboard and evaluates a number of the options for Mars, Venus and Titan aerobraking missions.
[View Full Paper]

AAS 11 – 478

The Next Generation of Mars-GRAM and Its Role in the Autonomous Aerobraking Development Plan

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The Mars Global Reference Atmospheric Model (Mars-GRAM) is an engineering-level atmospheric model widely used for diverse mission applications. Mars-GRAM 2010 is currently being used to develop the onboard atmospheric density estimator that is part of the Autonomous Aerobraking Development Plan. In previous versions, Mars-GRAM was less than realistic when used for sensitivity studies for Thermal Emission Spectrometer (TES) MapYear=0 and large optical depth values, such as tau=3. A comparison analysis has been completed between Mars-GRAM, TES and data from the Planetary Data System (PDS) resulting in updated coefficients for the functions relating density, latitude, and longitude of the sun. The adjustment factors are expressed as a function of height (z), Latitude (Lat) and areocentric solar longitude (Ls). The latest release of Mars-GRAM 2010 includes these adjustment factors that alter the input data from MGCM and MTGCM for the Mapping Year 0 (user-controlled dust) case. The greatest adjustment occurs at large optical depths such as tau >1. The addition of the adjustment factors has led to better correspondence to TES Limb data from 0-60 km as well as better agreement with MGS, ODY and MRO data at approximately 90-135 km. Improved simulations utilizing Mars-GRAM 2010 are vital to developing the onboard atmospheric density estimator for the Autonomous Aerobraking Development Plan. Mars-GRAM 2010 was not the only planetary GRAM utilized during phase 1 of this plan; Titan-GRAM and Venus-GRAM were used to generate density data sets for Aerobraking Design Reference Missions. These data sets included altitude profiles (both vertical and along a trajectory), GRAM perturbations (tides, gravity waves, etc.) and provided density and scale height values for analysis by other Autonomous Aerobraking team members. [View Full Paper]

SESSION 5: ASTEROID AND NEO II
Chair: Dr. Shyam Bhaskaran, Jet Propulsion Laboratory

AAS 11 – 440

A New Approach on the Long Term Dynamics of NEO's Under Yarkovsky Effect

Jesús Peláez, **Hodei Urrutxua**, **Claudio Bombardelli** and **Isabel Perez-Grande**, Technical University of Madrid (UPM), ETSI Aeronáuticos, Madrid, Spain

A classical approach to the many-body problem is that of using special perturbation methods. Nowadays and due to the availability of high-speed computers is an essential tool in Space Dynamics which exhibits a great advantage: it is applicable to any orbit involving any number of bodies and all sorts of astrodynamical problems, especially when these problems fall into regions in which general perturbation theories are absent. One such case is, for example, that Near Earth Objects (NEO's) dynamics. In this field, the Group of Tether Dynamics of UPM (GDT) has developed a new regularization scheme —called DROMO— which is characterized by only 8 ODE. This new regularization scheme allows a new approach to the dynamics of NEO's in the long term, specially appropriated to consider the influence of the anisotropic thermal emission (Yarkovsky and YORP effects) on the dynamics. A new project, called NEODROMO, has been started in GDT that aims to provide a reliable tool for the long term dynamics of NEO's. [View Full Paper]

AAS 11 – 441

A Survey of Potential Human-Precursor Robotic Asteroid Missions

Michael L. Cupples, Modeling & Simulation, Raytheon Missile Systems, Tucson, Arizona, U.S.A.; **Roberto Furfaro**, **Carl W. Hergenrother**, **Daniel R. Wibben** and **John N. Kidd Jr.**, University of Arizona, Tucson, Arizona, U.S.A.

A preliminary mission analyses survey of conceptual robotic asteroid missions that are precursor to potential human asteroid missions is provided, yielding a set of parametric data that can be used for preliminary mission planning. For a set of carefully chosen asteroids, this study generated a table of delta-v data that extends over a range of launch opportunity dates and a range of total transfer times. A subjective comparison of missions was performed and the comparison results are reported, further evaluating the low delta-v analyses data based on a set of Key Performance Parameters that included Earth departure energy (C3) and total transfer time, as well as total delta-v. The key parameter comparison yielded a table of data that synthesizes the rather large set of mission analyses data into a set of "best" cases. [View Full Paper]

AAS 11 – 442
(Paper Withdrawn)

AAS 11 – 443

Launch Analyses Supporting Conceptual Human-Precursor Robotic Asteroid Missions

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From a set of carefully selected asteroids, a study of conceptual asteroid missions was conducted using a stochastic direct search global optimization process, assuming a set of Key Performance Parameters (KPP's). The key parameters from the best case set included the minimum Escape Energy (C3) as well as the minimum mission total delta V for each asteroid, for both direct and gravity assisted missions. The objective of the current study to determine the launch window times required to achieve ascent and injection onto the outbound trajectory required for either the direct or gravity assisted mission to the selected asteroid, taking into consideration the impact of the range safety limits on the launch azimuths. A set of flyout trajectory orbital elements corresponding to the launch windows will be provided, and a preliminary assessment of the resulting launch vehicle payload delivery capability and margins will be conducted provided based on launch vehicle vendor data. [View Full Paper]

AAS 11 – 444

Methodology and Results of the Near-Earth Object (NEO) Human Space Flight (HSF) Accessible Targets Study (NHATS)

Brent W. Barbee, **Ronald G. Mink** and **Cassandra M. Alberding**, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Daniel R. Adamo**, Astrodynamics Consultant, Houston, Texas, U.S.A.

Near-Earth Asteroids (NEAs) have been identified by the Administration as potential destinations for human explorers during the mid-2020s. Planning such ambitious missions requires selecting potentially accessible targets from the growing known population of 8,008 NEAs. NASA is therefore conducting the Near-Earth Object (NEO) Human Space Flight (HSF) Accessible Targets Study (NHATS), in which the trajectory opportunities to all known NEAs are being systematically evaluated with respect to a set of defined constraints. While the NHATS algorithms have identified hundreds of NEAs which satisfy purposely inclusive trajectory constraints, only a handful of them offer truly attractive mission opportunities in the time frame of greatest interest. In this paper we will describe the structure of the NHATS algorithms and the constraints utilized in the study, present current study results, and discuss various mission design considerations for future human space flight missions to NEAs. [View Full Paper]

AAS 11 – 445

Mission Analysis and Transfer Design for the European Student Moon Orbiter

Willem van der Weg and **Massimiliano Vasile**, Advanced Space Concepts Laboratory, Department of Mechanical Engineering, University of Strathclyde, Scotland, U.K.

This paper presents an overview of the mission analysis performed for the European Student Moon Orbiter (ESMO). Scheduled for launch in 2014 – 2015 as a piggy-back payload, it is currently the only ESA planned mission to the Moon. The launch period was systemically scanned by an automatic transfer generation algorithm, which process is described herein, to compile a large database of nominal transfer options. The database contains 2 types of transfer; transfers with free starting conditions and transfers fixed to a certain launch hour and date using an Ariane 5 launch vehicle. ESMO is inserted into a highly eccentric frozen orbit at the Moon, to minimize the propellant used to insert into, and maintain, its lunar orbit. Between launch and actual departure from the Earth, ESMO will perform a series of apogee raising maneuvers that inject the spacecraft into a trans-lunar transfer within the limits of the current propulsion system.
[View Full Paper]

AAS 11 – 446

Near-Earth Asteroids Accessible to Human Exploration with High-Power Electric Propulsion

Damon Landau and **Nathan Strange**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The diverse physical and orbital characteristics of near-Earth asteroids provide progressive stepping stones on a flexible path to Mars. Beginning with cislunar exploration capability, the variety of accessible asteroid targets steadily increases as technology is developed for eventual missions to Mars. Noting the potential for solar electric propulsion to dramatically reduce launch mass for Mars exploration, we apply this technology to expand the range of candidate asteroid missions. The variety of mission options offers flexibility to adapt to shifting exploration objectives and development schedules. A robust and efficient exploration program emerges where a potential mission is available once per year (on average) with technology levels that span cislunar to Mars-orbital capabilities. Examples range from a six-month mission that encounters a 10-m object with 65 kW to a two-year mission that reaches a 2-km asteroid with a 350-kW system.
[View Full Paper]

AAS 11 – 447

Orbit Options for an Orion-Class Spacecraft Mission to a Near-Earth Object

Nathan C. Shupe and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Colorado, U.S.A.

This study seeks to identify candidate orbit options for a crewed mission to a Near-Earth Object (NEO) using an Orion-class spacecraft. A model including multiple perturbations (solar radiation pressure, solar gravity, non-spherical mass distribution of the central body) to two-body dynamics is constructed to numerically integrate the motion of a satellite in close proximity to a small body in an elliptical orbit about the Sun. Simulations about NEOs possessing various physical parameters (size, shape, rotation period) are then used to empirically develop general guidelines for establishing orbits of an Orion-class spacecraft about a NEO. [View Full Paper]

AAS 11 – 448

Small-Body Gravitational Field Approximation Methods

Parv Patel, **Robert Phillips** and **Bogdan Udrea**, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.

Small celestial bodies such as comets and asteroids are the target of space exploration missions which have invigorated noticeable interest in aerospace communities for nearby orbit designs. Among the requirements for planning such missions is an accurate model of their gravitational fields which serves even the most irregularly shaped bodies. This paper offers alternative approaches for generating gravity models of these bodies by using size-varying element approximations. The geometric models are explained and are evaluated for modeling and computational performance. Each gravity model is compared with that of a tetrahedron model to verify accuracy and reliability for practical applications. [View Full Paper]

AAS 11 – 449

Why Atens Enjoy Enhanced Accessibility for Human Space Flight

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Brent W. Barbee, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Near-Earth objects can be grouped into multiple orbit classifications, among them being the Aten group, whose members have orbits crossing Earth's with semi-major axes less than 1 astronomical unit. Atens comprise well under 10% of known near-Earth objects. This is in dramatic contrast to results from recent human space flight near-Earth object accessibility studies, where the most favorable known destinations are typically almost 50% Atens. Geocentric dynamics explain this enhanced Aten accessibility and lead to an understanding of where the most accessible near-Earth objects reside. Without a comprehensive space-based survey, however, highly accessible Atens will remain largely unknown. [View Full Paper]

SESSION 6: TRAJECTORY OPTIMIZATION I
Chair: David Dunham, KinetX, Inc.

AAS 11 – 450

Hypersonic, Aerodynamically Controlled, Path Constrained Reentry Optimization Using Pseudospectral Methods

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Anil V. Rao, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.

Hypersonic, aerodynamically controlled reentries are optimized with the *General Pseudospectral Optimal Control Software* (GPOPS). The reentries presented in this paper incorporate state and control path constraints and interior waypoint constraints to address heating, stability, and no-fly zone constraints. By examining multiple reentry profiles, GPOPS was used to determine the booster size needed to safely complete the desired mission objectives without being significantly oversized. GPOPS's newly developed mesh refinement scheme is used to adaptively adjust the mesh size and spacing to increase solution accuracy. The accuracy improvements afforded by the mesh refinement scheme are highlighted and the solution process is compared with past efforts on this problem using a different tool, SOCS. [View Full Paper]

AAS 11 – 451

A Design Method for Low Altitude, Near-Equatorial Lunar Orbits

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In 2013 the Lunar Atmosphere & Dust Environment Explorer (LADEE) mission will return to an orbital regime not visited since Apollo. The lunar orbit required for LADEE poses unique challenges to the mission designer: low, retrograde, near circular, near equatorial, 100 days duration, with the line of apsides aligned near the solar terminator. Due to the close proximity to the surface, the lunar gravity creates havoc on the LADEE orbit, perturbing the eccentricity and line of apsides while the semi-major axis remains largely unchanged. LADEE uses a novel, visual approach to allow the orbit designer to predict altitude decay and shifts in argument of periapsis and to plan orbit maintenance maneuvers. [View Full Paper]

AAS 11 – 452

(See Session 17)

AAS 11 – 453

New Dynamic Model for Lunar Probe and its Application to Quasi-Periodic Orbit about the Translunar Libration Point

Yingjing Qian, School of Astronautics Engineering, Harbin Institute of Technology, China and Visiting Scholar, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Inseok Hwang**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Wuxing Jing** and **Jian Wei**, School of Astronautics Engineering, Harbin Institute of Technology, China

A new dynamic model with the standard ephemerides that describes the relative motion of a lunar probe in a rotating coordinate system is presented. By using the ephemerides, the description for the real physical situation is more precise. Compared with other high-order models, the complexity of the proposed model is lower. More specifically, the proposed model considers the influences of direct and indirect Sun's perturbation, and the eccentricity of the Moon's orbit. It also provides a solution without a truncation error. Further, a lunar L2 quasiperiodic orbit design is presented as an application of the proposed model. The initial conditions are calculated by using the Lindstedt-Poincare technique. An iteration method which introduces the Sun's influence gradually and the differential correction are utilized to adjust the initial conditions.
[View Full Paper]

AAS 11 – 454

Lunar-Resonant Trajectory Design for the Interstellar Boundary Explorer (IBEX) Extended Mission

John Carrico Jr., **Donald Dichmann**, **Lisa Policastri**, **John Carrico III**, **Timothy Craychee**, **John Ferreira**, **Marissa Intelisano** and **Ryan Lebois**, Applied Defense Solutions, Inc., Fulton, Maryland, U.S.A.; **Mike Loucks**, Space Exploration Engineering Co., Friday Harbor, Washington, U.S.A.; **Travis Schrift** and **Ryan Sherman**, Applied Defense Solutions, Inc., Fulton, Maryland, U.S.A.

This paper describes the trajectory design and analysis performed to ensure the success of the IBEX extended mission. In order to minimize the radiation dose, improve science collection, and avoid long eclipses, the authors designed a transfer to a new orbit with a period of about 9.1 days, which yields a 3:1 resonance with the Moon's orbit. In June 2011, the IBEX flight team commanded IBEX to perform three maneuvers which successfully transferred IBEX to this new lunar-resonant orbit. This paper gives the details of the analysis, the trade-offs that were made, and the constraints that governed the operations. [View Full Paper]

AAS 11 – 455

Optimal Earth-Moon Transfer Trajectory Design Using Mixed Impulsive and Continuous Thrust

Daero Lee, **Tae Soo No** and **Ji Marn Lee**, Chonbuk National University, Jeonju, Republic of Korea; **Gyeong Eon Jeon**, School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Republic of Korea; **Ghangho Kim**, Korea Aerospace Research Institute, Daejeon, Republic of Korea; **Sang-Kon Lee**

Optimal transfer trajectories based on the planar circular restricted three body problem are designed using mixed impulsive and continuous thrust. The continuous, dynamic trajectory optimization is reformulated in the form of discrete optimization problem by the method of direct transcription and collocation, and is then solved using nonlinear programming software. Two very different transfer trajectories can be obtained by different combinations of the design parameters. Furthermore, it was found that all designed trajectories permit a ballistic capture by the Moon's gravity. Finally, the required thrust profiles are presented and analyzed in detail. [View Full Paper]

AAS 11 – 456

Parametric Study of Earth-to-Moon Transfers with Hybrid Propulsion System and Dedicated Launch

Giorgio Mingotti, Institut für Industriemathematik, Universität Paderborn, Paderborn, Germany

This work concerns preliminary parametric design of Earth-to-Moon transfers, exploiting both chemical (high-thrust) and solar electric (low-thrust) propulsion. Starting from a GTO to a polar orbit around the Moon, WSB trajectories with initial lunar swingby are evaluated in terms of propellant mass consumption and flight time. A dedicated launch strategy is investigated. This research has been conducted during an internship at the European Space Operations Centre, in the Mission Analysis Section, within the AstroNet framework. [View Full Paper]

AAS 11 – 457

Research of the Free-Return Trajectories between the Earth-Moon

Qinqin Luo, **Jianfeng Yin** and **Chao Han**, School of Astronautics, Beihang University, Beijing 100191, China

A new design method for the free-return lunar flyby trajectories between the Earth and the Moon is developed in this paper. The pseudostate theory is adopted to get the initial result of the free-return trajectory. On the basis of the initial result, an improved differential-correction method is employed to find the final solution in a more complicated dynamic model. The global features of the free-return lunar flyby trajectories are studied via the design method proposed in this paper, and some valuable results are obtained. [View Full Paper]

AAS 11 – 458

(Paper Withdrawn)

AAS 11 – 459

Targeting Low-Energy Transfers to Low Lunar Orbit

Jeffrey S. Parker and **Rodney L. Anderson**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

A targeting scheme is presented to build trajectories from a specified Earth parking orbit to a specified low lunar orbit via a low-energy transfer and up to two maneuvers. The total transfer ΔV is characterized as a function of the Earth parking orbit inclination and the departure date for transfers to each given low lunar orbit. The transfer ΔV cost is characterized for transfers constructed to low lunar polar orbits with any longitude of ascending node and for transfers that arrive at the Moon at any given time during a month. [View Full Paper]

AAS 11 – 470

Atmospheric Entry Guidance via Multiple Sliding Surfaces Control for Mars Precision Landing

Scott Selnick, Guidance Design & Performance, Raytheon Missile Systems, Tucson Arizona, U.S.A.; **Roberto Furfaro** and **Daniel R. Wibben**, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.

Improving Mars landing accuracy will require the implementation of robust, closed-loop guidance schemes for the entry portion of the atmospheric flight. A novel non-linear atmospheric entry guidance law has been developed for a class of low-lift landers similar to the one expected to be flown in the upcoming Mars Science Laboratory (MSL) mission. Here we proposed a Multiple Sliding Surface Guidance (MSSG) approach for Mars entry guidance. The presented guidance scheme is based on a higher order sliding mode control theory adapted to account for (1) the specific 2-sliding mode order exhibited by the longitudinal motion of the entry vehicle guided, using bank angle variations and (2) the ability of the system to reach the sliding surface in a finite time. Contrary to more standard methods designed to track a drag-based profile as a function of the range-to-go, the proposed scheme does not require any off-line trajectory generation and therefore it is suitable for real-time implementation. The global stability nature of the MSSG law is proven by using a Lyapunov-based approach. A parametric study has been conducted to understand the behavior of such class of trajectories as a function of the guidance parameters. The MSSG algorithm targeting ability is analyzed through a set of Monte Carlo simulations where the guidance law is required to operate under off-nominal conditions. Simulation results show good performance under perturbations and parameter uncertainties. [View Full Paper]

SESSION 7: FORMATION FLYING I
Chair: Dr. Aaron Trask, Apogee Integration

AAS 11 – 460
(Paper Withdrawn)

AAS 11 – 461
(Paper Withdrawn)

AAS 11 – 462

An Operational Methodology for Large Scale Deployment of Nanosatellites into Low Earth Orbit

Justin A. Atchison and **Aaron Q. Rogers**, Space Department, The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.; **Steven J. Buckley**, Operationally Responsive Space Office, Kirtland AFB, New Mexico, U.S.A.

The on-orbit deployment of large numbers of nanosatellites is cast in terms of the relative motion equations, augmented with differential drag. Using this framework, we develop a methodology for minimizing the likelihood of recontact or interference among the deployed nanosatellites. This approach is applied to the Operationally Responsive Space Office's Launch Enabler Mission, which is planning to deliver 25 small payloads to orbit in the mid-late 2012 timeframe. By strategically varying the deployment order, timing, and launch vehicle attitude, we demonstrate net separation amongst each of the nanosatellites for the first three weeks, as validated by high fidelity simulations. [View Full Paper]

AAS 11 – 463

Control of Relative Motion via State-Dependent Riccati Equation Technique

Giuseppe Di Mauro, **Pierluigi Di Lizia** and **Michèle Lavagna**, Aerospace Engineering Department, Politecnico di Milano, Milano, Italy

In this paper, development of a nonlinear controller based on State-Dependent Riccati Equation (SDRE) technique is investigated to solve relative motion control problem involving in a docking operations between two Earth orbiting spacecrafts as well as in a leader-follower formation keeping mission. This method allows to generate a sub-optimal control law to regulate the tracking error in relative position and attitude. Therefore the relative translational and attitude dynamics are modeled, considering the mutual coupling due to the external gravitational torques and the nonlinearity due to Earth oblateness and air drag effects. Numerical simulations are carried out to demonstrate the effectiveness of this control formulation. Particularly, three different approaches are proposed to implement the SDRE controller, that is *Power Series Formulation*, *Kleinman-Newton* and *Quasi-Newton* algorithms, and their effects on computational cost are analyzed. [View Full Paper]

AAS 11 – 464

Curvilinear Coordinates for Covariance and Relative Motion Operations

David A. Vallado and **Salvatore Alfano**, Analytical Graphics Inc., Center for Space Standards and Innovation, Colorado Springs, Colorado, U.S.A.

Relative motion studies have traditionally focused on linearized equations, and inserting additional force models into existing formulations to achieve greater fidelity. A simpler approach may be numerically integrating the two satellite positions and then converting to a modified equi-distant cylindrical frame as necessary. Recent works have introduced some approaches for this transformation as it applies to covariance operations, with some approximations. We develop an exact transformation between Cartesian and curvilinear frames and test the results for various orbital classes. The transformation has applicability to covariance operations which we also introduce. Finally, we examine how the transformation affects graphical depiction of the covariance matrix.
[View Full Paper]

AAS 11 – 465

Effective Sphere Modeling for Electrostatic Forces on Three-Dimensional Spacecraft Shapes

Lee E. Z. Jasper and **Hanspeter Schaub**, Aerospace Engineering Sciences Department, University of Colorado, Boulder, Colorado, U.S.A.

Satellite formations utilizing Coulomb forces are being studied due to their potential for their extremely low-fuel, low-power close formation flying control. Prior studies into Coulomb formations employ point charge or isolated sphere assumptions with well known electrostatic behavior. This is justified by having the custom Coulomb spacecraft assume near-spherical shapes to minimize charge densities for a given potential. Complex geometries, however, are the norm for existing satellite structures. This paper develops a method to model complex geometries as finite spheres. Finite element electrostatic field solutions are used to model the force interactions between a sphere and a non-spherical body. The effective sphere method is demonstrated on a sphere, a cylinder and a generic satellite structure. Force behavior is shown to match between the finite element solution and a 3D body's effective sphere for separation distances beyond 3 – 4 craft radii. Differences in the effective radii for the same non-spherical body are discussed along principal body axes and a near-elliptical distribution of effective radii are found for the case of a cylindrical shape. Finally, the nadir-aligned relative motion control of a cylinder-sphere formation is considered using the cylinder's effective radius and a voltage control strategy. [View Full Paper]

AAS 11 – 466

Relative Motion Control for Two-Spacecraft Electrostatic Orbit Corrections

Erik A. Hogan and **Hanspeter Schaub**, Aerospace Engineering Sciences Department, University of Colorado, Boulder, Colorado, U.S.A.

The charged relative motion dynamics and control of a two-craft system is investigated if one vehicle is performing a low-thrust orbit correction using inertial thrusters. The nominal motion is an along-track configuration where active electrostatic charge control is maintaining an attractive force between the two vehicles. In this study the charging is held fixed, and the inertial thruster of the tugging vehicle is controlled to stabilized the relative motion to a nominal fixed separation distance. Using a candidate Lyapunov function, the relative orbit control law of the tugging vehicle with respect to the passive vehicle is shown to be asymptotically stable. Analysis of the control system gains is performed in order to achieve a desired settling time and damping ratio. The effects of uncertainties in the vehicle charges are also examined. Using numerical simulation, the performance of the proposed control system is investigated for a formation in GEO. Results obtained from integration of the relative equations of motion are compared to full inertial simulations. [View Full Paper]

AAS 11 – 467

Nonlinear Analytical Solution of Relative Motion Subject to J_2 Perturbation Using Volterra Kernels

Ashraf Omran and **Brett Newman**, Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, Virginia, U.S.A.

This paper introduces Volterra theory to orbit mechanics. The paper presents a novel nonlinear analytical solution for the relative motion of two satellites subject to J_2 perturbation with a circular reference orbit. First, the nonlinear equations of the relative motion are expanded in a polynomial form using the Knocker operator. Carleman bilinearization is then used to compute Volterra kernels analytically in terms of the orbit parameters and the deputy initial conditions. The resultant solution based on these analytical Volterra kernels is compared to the linear solution showing a significant reduction in the error, when the nonlinear simulation is considered as the benchmark.
[View Full Paper]

AAS 11 – 468
(Paper Withdrawn)

AAS 11 – 469
(Paper Withdrawn)

SESSION 8: SPECIAL TOPIC: CONJUNCTION ASSESSMENT
Chair: Dr. Ryan Frigm, a.i. Solutions inc.

AAS 11 – 430

A Tuned Single Parameter for Representing Conjunction Risk

D. Plakalović, **M. D. Hejduk**, and **R. C. Frigm**, Mission Services Division, a.i. solutions, Inc., Colorado Springs, Colorado, U.S.A.; **L. K. Newman**, Robotic Systems Protection Program, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Satellite conjunction assessment risk analysis is a subjective enterprise that can benefit from quantitative aids and, to this end, NASA/GSFC has developed a fuzzy logic construct—called the F-value—to attempt to provide a statement of conjunction risk that amalgamates multiple indices and yields a more stable intra-event assessment. This construct has now sustained an extended tuning procedure against heuristic analyst assessment of event risk. The tuning effort has resulted in modifications to the calculation procedure and the adjustment of tuning coefficients, producing a construct with both more predictive force and a better statement of its error. [View Full Paper]

AAS 11 – 431

Analysis of Collision Avoidance Maneuver for COMS-1 Satellite

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The COMS-1 (Communication, Ocean and Meteorological Satellite 1 or Cheollian), the first geosynchronous satellite developed by the Republic of Korea, was successfully launched into its mission orbit by the Ariane in June, 2010 and has been under the operational control of the Korea Aerospace Research Institute (KARI). However, Russia's RADUGA 1-7 satellite has come close to the COMS-1 satellite, in its position at a longitude of 128.2 degrees East, since last January 2011. In this paper, the preparations for and results of collision avoidance maneuvers for the COMS-1 satellite are presented. The main problem in the preparation of the maneuver was the positional uncertainty of the RADUGA 1-7. The only source of orbital data for the RADUGA 1-7 was the published NORAD TLE sets, while the data for COMS-1 can be estimated using ranging data from the ground station located at KARI. In addition, the special perturbation (SP) data, which is more precise orbital data than that of the NORAD TLE sets based on the general perturbation model, were not available for both of the satellites at that time. Therefore, the mission control center had to use the NORAD TLE sets in order to generate the maneuvering plan, in spite of the low level of positional information for RADUGA 1-7. In this paper, we introduce a NORAD TLE based ground orbit determination strategy; efforts to increase the position accuracy of RADUGA 1-7 based on the proposed strategy are also presented. [View Full Paper]

AAS 11 – 432

Assessment of Uncertainty-Based Screening Volumes for NASA Robotic LEO and GEO Conjunction Risk Assessment

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Conjunction Assessment operations require screening assets against the space object catalog by placing a pre-determined spatial volume around each asset and predicting when another object will violate that volume. The selection of the screening volume used for each spacecraft is a trade-off between observing all conjunction events that may pose a potential risk to the primary spacecraft and the ability to analyze those predicted events. If the screening volumes are larger, then more conjunctions can be observed and therefore the probability of a missed detection of a high risk conjunction event is small; however, the amount of data which needs to be analyzed increases. This paper characterizes the sensitivity of screening volume size to capturing typical orbit uncertainties and the expected number of conjunction events observed. These sensitivities are quantified in the form of a trade space that allows for selection of appropriate screening volumes to fit the desired concept of operations, system limitations, and tolerable analyst workloads. This analysis will specifically highlight the screening volume determination and selection process for use in the NASA Conjunction Assessment Risk Analysis process but will also provide a general framework for other Owner / Operators faced with similar decisions. [View Full Paper]

AAS 11 – 433

Optimal Collision Avoidance for Multiple Conjunction Events

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Operational collision threat characterization is now an essential component of space mission operations. Most spacecraft operators have some semblance of a process to evaluate and mitigate high-risk conjunction events. As the size of the space object catalog increases, satellite operators will be faced with more conjunction events to evaluate. Thus more sophisticated collision threat characterization and collision avoidance strategies must be implemented. This paper presents an optimal avoidance methodology that reduces the collision risk for one or more high-risk conjunction events. The avoidance approach leverages a derivative-free optimization (DFO) algorithm. It is shown that the DFO method is particular well suited for optimal maneuver planning.
[View Full Paper]

AAS 11 – 434

Requirements and Guidance for Conjunction Assessment

David Finkleman, Center for Space Standards and Innovation, Analytical Graphics, Inc., Colorado Springs, Colorado, U.S.A.

This paper will review development of the content, format, implementation, and operational use of timely information for mitigating the consequences of conjunctions among satellites and trace the elements of information to requirements for dealing with threatening events. Stakeholders are developing essential elements of data, transmission formats, and operational guidance for managing close approaches (conjunctions) among satellites, preventing collisions, and mitigating the consequences of orbital events. The satellite operations community is also developing guiding principles for dealing with potential collisions in space. [View Full Paper]

AAS 11 – 435

Probability of Collision with Special Perturbations Dynamics Using the Monte Carlo Method

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Special perturbations-based Monte Carlo methods were used to investigate approaches for estimating the probability of collision between two satellites. Sample populations for each satellite are produced via the covariance at epoch, then each sample is propagated to the time span of interest where the closest point of approach between samples is determined. The output of the Monte Carlo analyses produce a cumulative distribution function of miss distance, which, given the combined radius of the two satellites, can be translated into a probability of collision estimate. Comparisons are made against an analytical method and a two-body Monte Carlo method for LEO and GEO orbit cases. Additionally, the impact of covariance realism is considered through the introduction of a scale factor to the covariance matrix. The results indicate that, although the analytic method matches the Monte Carlo methods at the time of closest approach for the LEO case, the probability of collision calculations are in error likely because the propagated Cartesian covariance used as input do not adequately represent the orbit error probability distributions; these errors may be smaller, however, than errors due to covariance realism in general. A high performance computing framework called Collision and Conjunction Analysis (CoCoA), using shared or distributed memory, was utilized to generate results in a timely manner. [View Full Paper]

AAS 11 – 436

Intelsat Experiences on Satellite Conjunctions and Lesson Learned

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In this paper we will present our recent experiences on satellite conjunctions and our end-to-end process to validate potential close approaches and if necessary to plan maneuvers to increase miss distances. We will discuss issues encountered from our experiences including (1) the selection of monitoring window to provide sufficient time to react to potential conjunctions while minimizing false alarms result from the degraded accuracies in the orbit solutions due to uncertainties and maneuver effects; (2) selection of conjunction threshold parameters to provide reliable conjunction assessments and the criteria and process for planning maneuvers to increase miss distances and (3) quality of conjunction assessments result from the uncertainties in the orbit solutions due to errors in the data processing (sensor biases, frame/time system conversion errors, modeling errors and etc…) We will also discuss other ideas for moving forward including (1) acquiring third party data to validate orbit uncertainties, (2) data fusion to improve orbit solutions accuracies and uncertainties, (3) different conjunction detection techniques and selection of thresholds to provide more reliable assessments and (4) techniques to monitor miss distances to help validate potential close approaches. We will present the different studies and analyses that we have conducted to improve satellite conjunction monitoring and mitigations including (1) sensitivity studies and covariance analyses showing the benefits of combing measurement data from different measurements types; (2) an experimental data weight technique to determine the optimal relative data weights for data fusion and to estimate the realistic uncertainties in the final orbit solutions and (3) an idea for monitoring miss distances during satellite close approaches.

[View Full Paper]

AAS 11 – 437

Sequential Probability Ratio Test for Collision Avoidance Maneuver Decisions Based on a Bank of Norm-Inequality-Constrained Epoch-State Filters

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Sequential probability ratio tests explicitly allow decision makers to incorporate false alarm and missed detection risks, and are potentially less sensitive to modeling errors than a procedure that relies solely on a probability of collision threshold. Recent work on constrained Kalman filtering has suggested an approach to formulating such a test for collision avoidance maneuver decisions: a filter bank with two norm-inequality-constrained epoch-state extended Kalman filters. One filter models the null hypothesis that the miss distance is inside the combined hard body radius at the predicted time of closest approach, and one filter models the alternative hypothesis. The epoch-state filter developed for this method explicitly accounts for any process noise present in the system. The method appears to work well using a realistic example based on an upcoming highly-elliptical orbit formation flying mission. [View Full Paper]

AAS 11 – 438

Toroidal Path Filter

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For satellite conjunction prediction containing many objects, timely processing can be a concern. Various filters are used to identify orbiting pairs that cannot come close enough over a prescribed time period to be considered hazardous. Such pairings can then be eliminated from further computation to quicken the overall processing time. One such filter is the orbit path filter (also known as the geometric pre-filter), designed to eliminate pairs of objects based on characteristics of orbital motion. The goal of this filter is to eliminate pairings where the distance (geometry) between their orbits remains above some user-defined threshold, irrespective of the actual locations of the satellites along their paths. Rather than using a single distance bound, this work presents a toroid approach, providing a measure of versatility by allowing the user to specify different in-plane and out-of-plane bounds for the path filter. The primary orbit is used to define a focus-centered elliptical ring torus with user-defined thresholds. An assessment is then made to determine if the secondary orbit can touch or penetrate this torus. The method detailed here can be used on coplanar, as well as non-coplanar, orbits.
[View Full Paper]

AAS 11 – 439

Verifying Observational Data for Real-World Space Situational Awareness

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In practice, Space Situational Awareness (SSA) requires precise knowledge of all objects in orbit. A complete, robust and accurate SSA system is necessary for accurate conjunction analysis (CA) and Radio Frequency Interference (RFI) determination. The Space Data Association fuses data from multiple sources to support state-of-the-art CA and RFI operations. Implementation requires significant work including a detailed verification effort to monitor and ensure interoperability and compatibility. This paper summarizes the various data assembly, conversion, and OD operations to support this effort. The attention to detail required at each step is shown, including the effect that time and coordinate systems have on a computed conjunction. [View Full Paper]

SESSION 9: NON-EARTH ORBITING MISSIONS
Chair: Dennis Byrnes, Jet Propulsion Laboratory

AAS 11 – 479

A 3D Shape-Based Approximation Method for Low-Thrust Trajectory Design

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Mission design using low-thrust propulsion requires a method for approximating the spacecraft's optimal trajectory and its cost. The approximating method can be for the purpose of evaluating a large search space or for providing a suitable initial guess to be used with trajectory optimizers. Direct transcription methods are more likely to converge when given an initial guess satisfying the equation of motion constraints and the terminal boundary conditions. A shape-based method is derived here that is capable of determining such trajectories in three dimensions. An equivalent to the Lambert solver is therefore devised for low thrust transfers. Additionally, a throttle parameter is introduced such that the thrust acceleration equation of motion is satisfied. When combined with a genetic algorithm, it is possible to find solutions within a few percent of optimal by adjusting the free parameters of the problem. The algorithm is tested on an Earth-Mars rendezvous mission. [View Full Paper]

AAS 11 – 480

Comparisons between Newton-Raphson and Broyden’s Methods for Trajectory Design Problems

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Broyden’s method, a generalized-secant method for root-finding, was recently added as an option in the STK/Astrogator maneuver planning and trajectory design software module. The software previously used a Newton-Raphson approach with numerical partials to solve shooting problems. In this paper, the two methods are compared for a wide variety of problems, including stationkeeping, orbit transfers, and interplanetary trajectories. For most use-cases, Broyden’s method has a faster performance than Newton-Raphson. [View Full Paper]

AAS 11 – 481

End-to-End Trajectory Design for a Chemical Mission Including Multiple Flybys of Jovian Trojan Asteroids

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Missions to Jupiter’s L_4 Trojan asteroids have been recently proposed by several space agencies. A methodology for the end-to-end trajectory design of a chemical mission with a Soyuz launch and including as many flybys of Trojan asteroids as possible has been developed at CNES. Different options have been considered for the interplanetary cruise. Moreover, a branch-and-prune algorithm has been implemented for determining the fly-by sequences inside the swarm. Our results include a large amount of trajectories visiting up to four asteroids, as well as some with five asteroid flybys, which is a considerable achievement for a medium-size mission using chemical propulsion. [View Full Paper]

AAS 11 – 482

EPOXI Trajectory and Maneuver Analyses

Min-Kun J. Chung, **Shyamkumar Bhaskaran**, **Steven R. Chesley**, **C. Allen Halsell**, **Clifford E. Helfrich**, **David C. Jefferson**, **Timothy P. McElrath**, **Brian P. Rush**, **Tseng-Chan M. Wang** and **Chen-wan L. Yen**, Mission Design & Navigation Section, Jet Propulsion Laboratory, Pasadena, California, U.S.A.

The EPOXI mission is a NASA Discovery Mission of Opportunity combining two separate investigations: Extrasolar Planet Observation and Characterization (EPOCh) and Deep Impact eXtended Investigation (DIXI). Both investigations reused the DI instruments and spacecraft that successfully flew by the comet Tempel-1 (4 July 2005). For EPOCh, the goal was to find exoplanets with the high resolution imager, while for DIXI it was to fly by the comet Hartley 2 (4 Nov 2010). This paper documents the navigation experience of the earlier maneuver analyses critical for the EPOXI mission including statistical ΔV analyses and other useful analyses in designing maneuvers. It also recounts the trajectory design leading up to the final reference trajectory to Hartley 2.
[View Full Paper]

AAS 11 – 483

Ground Optical Navigation for the Stardust-NExT Mission to Comet 9P/Tempel 1

Stephen D. Gillam, **J. Ed. Riedel**, **William M. Owen Jr.**, **Tseng-Chan Mike Wang**, **Robert A. Werner**, **Shyam Bhaskaran**, **Steven R. Chesley**, **Paul F. Thompson** and **Aron A. Wolf**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Ground-based optical navigation (OpNav) using pictures taken by the Navigation camera on the Stardust spacecraft provided the target-relative information needed to design maneuvers during its approach to comet Tempel 1. Hardware problems, limited downlink bandwidth, and changes in the flight profile affected the OpNav picture schedule, sometimes in near-real time. The Stardust navigation camera and attitude control presented challenges. Picture-processing techniques were developed during approach that included background estimation, co-addition, and co-registration. These techniques, along with adaptive picture scheduling, successfully addressed the challenges. [View Full Paper]

AAS 11 – 484

Hayabusa: Navigation Challenges for Earth Return

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Hayabusa was a JAXA sample-return mission to Itokawa navigated, in part, by JPL personnel. The spacecraft survived several near mission-ending failures at Itokawa yet returned to Earth with an asteroid regolith sample on June 13, 2010. This paper describes NASA/JPL's participation in the Hayabusa mission during the last 100 days of its mission, wherein JPL provided tracking data and orbit determination, plus verification of maneuver design and entry, descent and landing. [View Full Paper]

AAS 11 – 485

Long Term Missions at the Sun-Earth Libration Point L1: ACE, SOHO, and WIND

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Three heliophysics missions—the Solar Heliospheric Observatory (SOHO), the Advanced Composition Explorer (ACE), and the Global Geoscience WIND—have been orbiting the Sun-Earth interior libration point L1 continuously since 1996, 1997, and 2004, respectively. ACE and WIND (both NASA missions) and SOHO (an ESA-NASA joint mission) are all operated from the NASA Goddard Space Flight Center Flight Dynamics Facility. While ACE and SOHO have been dedicated libration point orbiters since their launches, WIND prior to 2004 flew a remarkable 10-year deep-space trajectory that featured 38 targeted lunar flybys. The L1 orbits and the mission histories of the three spacecraft are briefly reviewed, and the station-keeping techniques and orbit maneuver experience are discussed. [View Full Paper]

AAS 11 – 486

Navigation of the EPOXI Spacecraft to Comet Hartley 2

Shyam Bhaskaran, **Matt Abrahamson**, **Steven Chesley**, **Min-Kun Chung**, **Allen Halsell**, **Robert Haw**, **Cliff Helfrich**, **David Jefferson**, **Brian Kennedy**, **Tim McElrath**, **William Owen**, **Brian Rush**, **Jonathon Smith**, **Tseng-Chan Wang** and **Chen-Wan Yen**, Navigation and Mission Design Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

On November 4, 2010, the EPOXI spacecraft flew by the comet Hartley 2, marking the fourth time that a NASA spacecraft successfully captured high resolution images of a cometary nucleus. EPOXI is the extended mission of the Deep Impact mission, which delivered an impactor on comet Tempel-1 on July 4, 2005. EPOXI officially started in September 2007 and eventually took over 3 years of flight time and had 3 Earth gravity assists to achieve the proper encounter conditions. In the process, the mission was redesigned to accommodate a new comet as the target and changes in the trajectory to achieve better imaging conditions at encounter. Challenges in navigation of the spacecraft included precision targeting of several Earth flybys and the comet encounter, uncertainties in determining the ephemeris of the comet relative to the spacecraft, and the high accuracy trajectory knowledge needed to image the comet during the encounter. This paper presents an overview of the navigation process used for the mission. [View Full Paper]

AAS 11 – 487

Particle Levitation, Trajectories, and Mass Transfer in the Quasi-Statically Charged, Planar Circular Restricted Four Body Problem

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In this paper, we discuss levitation conditions, orbits, and mass transfer of charged particles in a binary asteroid system, in which the asteroids are electrically charged due to solar radiation pressures. The surface potential of the asteroids is assumed to be a piece-wise function, with positive potential on the sunlit half and negative potential on the shadow half. We derive the nonautonomous equations of motion for charged particles and an analytic representation for their levitation conditions. Particle trajectories and temporary relative equilibria are examined in relation to their *osculating forbidden regions*, a concept we define and discuss. Finally, we use a Monte Carlo simulation to quantify expected mass transfer and loss rates between the asteroids. [View Full Paper]

AAS 11 – 488

Sun-Earth Based Spin Axis Determination for Interplanetary Missions and Its Application to IKAROS

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This paper describes an attitude determination strategy for spinner spacecraft based on the Sun and the Earth angles. This method realizes a complete spin vector determination using only one sun sensor. Thus this method is suitable for low cost, resource-limited spacecraft with a moderate attitude determination accuracy requirement. The method has been developed for and is actually used in IKAROS, which is a Japanese interplanetary solar sail demonstration mission. This paper introduces theoretical backgrounds of Sun-Earth based attitude determination and shows how the actual implementation was done in the IKAROS mission. Then the attitude determination performance achieved during the actual operation is evaluated. [View Full Paper]

SESSION 10: FORMATION FLYING II
Chair: Bo Naasz, NASA Goddard Space Flight Center

AAS 11 – 489
Carrier Phase Differential GPS for LEO Formation Flying – The PRISMA and TanDEM-X Flight Experience

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The paper describes recent accomplishments in the field of carrier phase based differential GPS navigation of multiple spacecraft based on practical mission experience. Following long years of research and laboratory experimentation, the technology has ultimately found its way into orbit and constitutes an indispensable contribution to the first European formation flying missions. While TanDEM-X relies on a high-precision post-facto reconstruction of the relative spacecraft position for interferometric SAR processing, the PRISMA mission makes use of differential GPS for real-time navigation and orbit control. Actual flight data are presented along with a discussion of the achieved performance and current limitations. [View Full Paper]

AAS 11 – 490
Fixed-Duration, Free Departure Time Satellite Formation Transfer Problem

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Satellite transfer between two satellite formations has its own features compared to satellite transfer between two earth-centered orbits. Based on these features, this paper formulates the transfer between two satellite formations as a fixed-duration, free departure time satellite transfer problem. General necessary conditions and transversality conditions of an extremal are given for this new type of problem. Simplified statements of this new problem are provided for three types of satellite engines. Moreover, analytic solutions at two specific cases are derived and used to support the theory of this paper. [View Full Paper]

AAS 11 – 491

Formation Flying along a Circular Orbit with Control Constraints

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In this paper, leader-follower formation flying problems based on the periodic orbits of the Hill-Clohessy-Wiltshire equations are considered. For a given final relative orbit, the admissible controls are feedback controls such that the follower tracks the final orbit asymptotically. The main performance index is the L_1-norm of the control input which is proportional to the fuel consumption. The L_∞-norm, which gives the magnitude of the input, is an additional performance index under the thruster level limitation. Feedback controls are designed via two algebraic Riccati equations with parameters, and their L_1- and L_∞- norms are given as functions of the parameters. Suboptimal controls are designed by choosing appropriate parameters. Simulation results for a reconfiguration problem are given to demonstrate the effectiveness of the design method. [View Full Paper]

AAS 11 – 492

Metrics for Mission Planning of Formation Flight

Shawn E. Allgeier and **Norman G. Fitz-Coy**, Mechanical & Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.; **Scott Erwin** and **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico, U.S.A.

This paper considers the analysis of relative motion between two spacecraft in orbit. Specifically, the paper seeks to provide bounds for relative spacecraft position- and velocity-based measures which impact spacecraft formation-flight mission design and analysis. The cross track (out of plane) separation and relative speed metrics for formation-flight are presented. A methodology for bounding the two metrics is presented. The extremal equations for the relative speed metric are formulated as an affine variety and solved using a Gröbner basis reduction. A numerical example is included to demonstrate the efficacy of the method. The metrics have utility to the mission designer of formation flight architectures, with relevance to Earth observation constellations and inter-satellite communications systems. [View Full Paper]

AAS 11 – 493

Natural Regions Near the Sun-Earth Libration Points Suitable for Space Observations with Large Formations

Aurélie Héritier and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana

This investigation explores regions near libration points that might prove suitable for space observations with large formations. Recent analyses have considered occulters located at relatively large distances from the telescope near the L_2 Sun-Earth libration point for detection of exoplanets. During the science mode, the telescope-occulter distance, as well as the pointing direction toward the star, are typically fixed. Quasi-periodic Lissajous trajectories are employed as a tool to determine regions near the telescope orbit where the large formation can be maintained. By placing the occulter in these locations, the control required to maintain the line-of-sight is reduced.
[View Full Paper]

AAS 11 – 494
(Paper Withdrawn)

AAS 11 – 495

Osculating Relative Orbit Elements Describing Relative Satellite Motion about an Eccentric Orbit

Joshuah A. Hess, National Air and Space Intelligence Center, Space Analysis Squadron, WPAFB, Ohio, U.S.A.; **Douglas D. Decker**, Science Applications International Corporation; **Thomas Alan Lovell**, U.S. Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, New Mexico, U.S.A.

Relative orbit elements (ROEs) based on a circular chief satellite orbit are erroneous when applied to a perturbed, non-circular reference orbit. In those situations, the ROEs will encounter geometric instability and drift. To counter this, a set of time-variant ROEs have been derived via state substitution to describe the relative orbit for the unperturbed, elliptical chief. A highly coupled relationship is found that describes the relative trajectory to higher accuracy taking numerical integration as the truth model. The eccentric ROEs describe a mathematically abstract, osculating ellipsoid that is inherently similar to classical Clohessy-Wiltshire results. [View Full Paper]

AAS 11 – 496

Osculating Relative Orbit Elements Describing Relative Satellite Motion with J_2 Perturbations

Joshuah A. Hess, National Air and Space Intelligence Center, Space Analysis Squadron, WPAFB, Ohio, U.S.A.; **Douglas D. Decker**, Science Applications International Corporation; **Thomas Alan Lovell**, U.S. Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, New Mexico, U.S.A.

Relative orbit elements (ROEs) based on a circular chief satellite orbit are erroneous when applied to a more realistic perturbed or non-circular reference orbit. In those situations, the ROEs will encounter geometric instability and drift. This paper aims to increase the applicability of ROEs by investigating the effects of the J_2 zonal harmonic on the relative trajectory. The perturbing effects are shown to introduce periodic effects to previously constant ROEs while compounding their secular variations.
[View Full Paper]

AAS 11 – 497

Satellite Relative Motion in Elliptical Orbit Using Relative Orbit Elements

Chao Han and **Jianfeng Yin**, School of Astronautics, Beihang University, Beijing, China

In this paper, using the spherical geometry, the relative orbit elements are strictly defined through the employment of a projection rule. The exact transformation equations between relative orbit elements and absolute orbit elements are deduced. A new relative motion model with no singularity based on relative orbit elements is derived, which is suitable for both elliptical and near-circular cases. The characteristics of elliptical relative motion are analyzed. The proposed method and conclusions are validated through numerical examples. The basic theory of relative orbit elements is improved and a unified model of both elliptical and near-circular relative motion is developed.
[View Full Paper]

AAS 11 – 498

Circular Orbit Radius Control Using Electrostatic Actuation for 2-Craft Configurations

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Electrostatic static actuation of free-flying spacecraft is being considered to directly control spacecraft relative motion. This paper investigates the effectiveness of using active electrostatic charging to perform orbit altitude adjustments of a nominally circular orbit. Coulomb forces are employed to gently pull a charged object in the along track direction. In contrast to prior work, this study uses an enhanced electrostatic force model which accounts for the increased capacitance of an object if another charged object is nearby with opposite charge polarity. The pulling configuration is shown to provide larger electrostatic forces over a pushing configuration due to the coupled capacitance modeling. Variational equations are developed to estimate the semi-major axis changes if spherical objects with controlled electrostatic potentials are actuated in the along-track direction. Numerical sweeps are performed to illustrate that kilo-Volt levels of potential are sufficient to achieve kilometer level radius changes per orbit for geosynchronous orbit regimes. [View Full Paper]

SESSION 11: ORBIT ESTIMATION I

Chair: Dr. Michael Gabor, Northrop Grumman

AAS 11 – 499

Advanced Navigation Strategies for an Asteroid Sample Return Mission

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The proximity operations phases of a sample return mission to an asteroid have been analyzed using advanced navigation techniques derived from experience gained in planetary exploration. These techniques rely on tracking types such as Earth-based radio metric Doppler and ranging, spacecraft-based ranging, and optical navigation using images of landmarks on the asteroid surface. Navigation strategies for the orbital phases leading up to sample collection, the touch down for collecting the sample, and the post sample collection phase at the asteroid are included. Options for successfully executing the phases are studied using covariance analysis and Monte Carlo simulations of an example mission to the near Earth asteroid 4660 Nereus. Two landing options were studied including trajectories with either one or two burns from orbit to the surface. Additionally, a comparison of post-sample collection strategies is presented. These strategies include remaining in orbit about the asteroid or standing-off a given distance until departure to Earth. [View Full Paper]

AAS 11 – 500
(Paper Withdrawn)

AAS 11 – 501
Fast, Efficient and Adaptive Interpolation of the Geopotential

Nitin Arora and **Ryan P. Russell**, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.

Conventional high-fidelity geopotential computations rely on expensive spherical harmonics (SH) series. In this study an interpolation scheme is proposed that classically improves compute speed at the expense of memory. The approach is exact in the sense that accelerations are calculated naturally as the gradient of the fitted potential, and continuity and smoothness to arbitrary order are ensured across local cells using the Junkins weight functions. Millions of local interpolating functions are chosen with a new adaptive method that minimizes coefficient storage subject to a maximum error threshold. Analytic inversions of the normal equations associated with each candidate interpolant allow for rapid solutions to the least squares process without resorting to the conventional numerical linear system solvers. Accordingly, time is afforded to cycle through hundreds of candidate interpolants for each of the millions of nodes, resulting in a global model with a highly optimized memory requirement and uniform error distribution. Speed is ensured by choosing simple polynomials as candidate interpolants. For example, the interpolation approach (deemed FETCH) fitting the full GRACE02C 200 x 200 spherical harmonics (SH) field requires 1.8 Gigabytes of memory and achieves over 300x speedups compared to a Pines SH implementation. The error profile of the interpolation model is adaptively selected throughout the global domain to conservatively mirror the published expected errors of the SH fitting function.
[View Full Paper]

AAS 11 – 502
Gravity Error Compensation Using Second-Order Gauss-Markov Processes

Jason M. Leonard, **Felipe G. Nievinski** and **George H. Born**, Department of Aerospace Engineering, University of Colorado, Boulder, Colorado, U.S.A.

Earth science satellite missions currently require orbit determination solutions with position accuracies to within a centimeter. The estimation of empirical accelerations has become commonplace in precise orbit determination (POD) for Earth-orbiting satellites. Dynamic model compensation (DMC) utilizes an exponentially time-correlated system noise process, known as a first-order Gauss-Markov process (GMP1) to estimate un-modeled accelerations. In this work, we address the use of a second-order Gauss-Markov process to compensate for higher order spherical harmonic gravity accelerations, beyond J_3. Improvements in POD and orbit prediction through the implementation of an optimal GMP2 for empirical acceleration estimation are assessed. The use of a single well calibrated GMP2 outperformes a GMP1 and a poorly calibrated GMP2 for both continuous observations and poor tracking data. [View Full Paper]

AAS 11 – 503

Navigation Analysis for an L_5 Mission in the Sun-Earth System

Pedro J. Llanos and **Gerald R. Hintz**, Astronautical Engineering Department, University of Southern California, Los Angeles, California, U.S.A.;
James K. Miller, Navigation Consultant, Los Angeles, California, U.S.A.

In a previous paper, we characterized a typical mission in a planar orbit around L_5 to observe the Sun. We indicated that such a mission is in fact feasible. In this paper, we provide a maneuver and orbit determination analysis for a L_5 mission. This study will be performed for both the transfer trajectory and the Trojan orbit around L_5. Orbit determination will be needed to have a more accurate estimation of the trajectory of the spacecraft at different stages: launch, mid-course, arrival and Trojan orbit. Therefore, we will analyze the required propulsion maneuvers needed to compensate primarily for injection errors at launch and station keeping maneuvers around L_5. [View Full Paper]

AAS 11 – 504
(Paper Withdrawn)

AAS 11 – 505
(Paper Withdrawn)

AAS 11 – 506

Orbit Determination Results of Akatsuki, (Planet-C) Mission –Venus Climate Orbiter–

Tsutomu Ichikawa, **Nobuaki Ishii**, **Hiroshi Takeuchi**, **Makoto Yoshikawa**, **Takaji Kato**, Japan Aerospace Exploration Agency (JAXA), Chuo-ku, Kanagawa, Japan; **Chiaki Aoshima**, **Tomoko Yagami** and **Yusuke Yamamoto**, Fujitsu Limited, Chiyoda-ku, Tokyo, Japan

"Akatsuki" mission has been launched on May 21, 2010 on an H-IIA booster from Tanegashima Space Center (TSC), Kagoshima, Japan, and arrived at Venus on December 6, 2010, without trouble, after cruising interplanetary approximately seven months. In this paper, the orbit determination result, the estimation strategy, and experiences during the period from the launch through the VOI (Venus Orbit Insertion) phase are discussed. [View Full Paper]

AAS 11 – 507

Re-Examination of Pioneer 10 Tracking Data Including Spacecraft Thermal Modeling

Dario Modenini and **Paolo Tortora**, Department of Mechanical and Aerospace Engineering (DIEM), University of Bologna, Forlì, Italy

The so-called Pioneer Anomaly is an anomalous shift in the radio-metric tracking signals received by Pioneer 10 and 11 spacecrafts, which *can* be ascribed to an approximately constant sunward acceleration acting on the probes. This anomalous acceleration has a similar magnitude for the two spacecraft, firstly reported by Anderson and al. in 1998, to be $(8.74 \pm 1.33) \cdot 10^{-10}$ m/s^2.

Since then, the existence of the anomaly has been confirmed independently by several groups and a large effort was devoted to find its origin providing, however, no definitive answers. The present study, carried out at the Radio Science lab of the University of Bologna in Forlì consists of two main parts: thermal modeling of the spacecraft throughout its trajectory, and orbit determination analysis. Based on existing documentation and recovered telemetry data, we built a finite element model of the spacecraft, whose complexity has been constrained to a degree allowing for sensitivity analysis.

The trajectory analysis has been performed using JPL's ODP (Orbit Determination Program) available to the University of Bologna thanks to a NASA/ASI bilateral agreement. Results show that orbital solutions may be achieved that do not require any anomalous acceleration other than the one of thermal origin. [View Full Paper]

AAS 11 – 508

Validation of COMS Satellite Orbit Determination Based on Single Station Antenna Tracking Data

Yoola Hwang and **Byoung-Sun Lee**, Satellite System Research Team, Electronics and Telecommunications Research Institute (ETRI), Daejeon, Republic of Korea; **Hae-Yeon Kim** and **Bang-Yeop Kim**, Geostationary Satellite Operation Team, Korea Aerospace Research Institute (KARI), Daejeon, Republic of Korea; **Haedong Kim**, Department of Aerospace Engineering, Sejong University, Seoul, Republic of Korea

A precise azimuth bias correction of the geostationary communication, ocean and meteorological satellite (COMS) is introduced and validated by orbit determination (OD) evaluation in this paper. Since COMS is located near the longitude of the ground control center, there is a singularity in geometry observables of azimuth direction. Azimuth bias of real tracking data can be eliminated using the external station's ranging data and predicted simulation data after OD. The accuracy of COMS OD employing the corrected azimuth data is tested by various OD validation methods. For an absolute accuracy confidence, the optical telescope scanning result is compared to the COMS ground track of longitude and latitude. The accuracy of COMS OD using a single station's tracking data satisfies within 5-6 km root-sum-squares (RSS) given by specifications when compared with two ranging OD results. [View Full Paper]

SESSION 12:
SPECIAL TOPIC: ARTEMIS MISSION
Chair: David Folta, NASA Goddard Space Flight Center

AAS 11 – 509

ARTEMIS Lunar Orbit Insertion and Science Orbit Design through 2013

Stephen B. Broschart, **Theodore H. Sweetser**, and **Vassilis Angelopoulos**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **David C. Folta** and **Mark A. Woodard**, Navigation & Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.;

As of late-July 2011, the ARTEMIS mission is transferring two spacecraft from Lissajous orbits around Earth-Moon Lagrange Point #1 into highly-eccentric lunar science orbits. This paper presents the trajectory design for the transfer from Lissajous orbit to lunar orbit insertion, the period reduction maneuvers, and the science orbits through 2013. The design accommodates large perturbations from Earth's gravity and restrictive spacecraft capabilities to enable opportunities for a range of heliophysics and planetary science measurements. The process used to design the highly-eccentric ARTEMIS science orbits is outlined. The approach may inform the design of future eccentric orbiter missions at planetary moons. [View Full Paper]

AAS 11 – 510

ARTEMIS Mission Overview: From Concept to Operations

David Folta, Navigation & Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Theodore Sweetser**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

ARTEMIS (Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun) repurposed two spacecraft to extend their useful science (Angelopoulos, 2010) by moving them via lunar gravity assists from elliptical Earth orbits to L_1 and L_2 Earth-Moon libration orbits and then to lunar orbits by exploiting the Earth-Moon-Sun dynamical environment. This paper describes the complete design from conceptual plans using weak stability transfer options and lunar gravity assist to the implementation and operational support of the Earth-Moon libration and lunar orbits. The two spacecraft of the ARTEMIS mission will have just entered lunar orbit at this paper's presentation. [View Full Paper]

AAS 11 – 511

Design and Implementation of the ARTEMIS Lunar Transfer Using Multi-Body Dynamics

David Folta and **Mark Woodard**, Navigation & Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Theodore Sweetser** and **Stephen B. Broschart**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **Daniel Cosgrove**, Space Sciences Laboratory, University of California, Berkeley, California, U.S.A.

The use of multi-body dynamics to design the transfer of spacecraft from Earth elliptical orbits to the Earth-Moon libration (L_1 and L_2) orbits has been successfully demonstrated by the Acceleration Reconnection and Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission. Operational support of the two ARTEMIS spacecraft is a final step in the realization of a design process that can be used to transfer spacecraft with restrictive operational constraints and fuel limitations. The focus of this paper is to describe in detail the processes and implementation of this successful approach. [View Full Paper]

AAS 11 – 512

(Paper Withdrawn)

AAS 11 – 513

Evaluating Orbit Determination Post-Processing Methods for Operational ARTEMIS Data

Bradley W. Cheetham and **George H. Born**, Colorado Center for Astrodynamics Research, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

Operating in the highly dynamic Earth-Moon libration point orbit (LPO) region, which is predominantly perturbed by the Earth, the Moon, and the Sun, is a challenge. The Artemis mission operated by the NASA Goddard Space Flight Center and the University of California at Berkeley recently became the first to ever maintain orbits in this regime. The resulting operational data provides significant opportunity for analysis to better understand these orbits and their operational constraints. Future efforts to quantify orbit determination results, recover un-modeled accelerations, realistic uncertainty propagation, and ultimately LPO utilization will grow out of an ability to post-process this operational data for further understanding of the dynamics involved. To prepare for post-processing of this data, this paper quantifies the effects of various contributors to the dynamic models, experimentally models errors in a simulated environment, and outlines areas of future focus. Realistic spacecraft ephemeris and attribute information will be used to the maximum extent possible. Simulations of orbit determination efficacy are performed using the Analytical Graphics Inc. Orbit Determination Tool Kit (ODTK) with appropriate tracking and spacecraft characteristics and known error sources.
[View Full Paper]

AAS 11 – 514

Orbit Determination of Spacecraft in Earth-Moon L1 and L2 Libration Point Orbits

Mark Woodard and **David Folta**, Navigation & Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Daniel Cosgrove**, **Jeffrey Marchese** and **Brandon Owens**, Space Sciences Laboratory, University of California, Berkeley, California, U.S.A.; **Patrick Morinelli**, Flight Dynamics Facility, Honeywell Technology Solutions Inc., Greenbelt, Maryland, U.S.A.

The ARTEMIS mission, part of the THEMIS extended mission is the first to fly spacecraft in the Earth-Moon Lissajous regions. In order to effectively perform lunar Lissajous station-keeping maneuvers, the ARTEMIS operations team has provided orbit determination solutions with typical accuracies on the order of 0.1 km in position and 0.1 cm/s in velocity. The ARTEMIS team utilizes the Goddard Trajectory Determination System (GTDS), using a batch least squares method, to process range and Doppler tracking measurements from the NASA Deep Space Network (DSN), Berkeley Ground Station (BGS), Merritt Island (MILA) station, and United Space Network (USN). The team has also investigated processing of the same tracking data measurements using the Orbit Determination Tool Kit (ODTK) software, which uses an extended Kalman filter and recursive smoother to estimate the orbit. The orbit determination results from each of these methods will be presented and we will discuss the advantages and disadvantages associated with using each method in the lunar Lissajous regions. In addition, we used the Orbit Determination Error Analysis System (ODEAS) to perform covariance analyses using various tracking data schedules. From this analysis, it was determined that 3.5 hours of DSN TRK-2-34 range and Doppler tracking data every other day would suffice to meet the predictive orbit knowledge accuracies in the Lissajous region.
[View Full Paper]

AAS 11 – 515

Stationkeeping of the First Earth-Moon Libration Orbiters: The ARTEMIS Mission

David C. Folta and **Mark A. Woodard**, Navigation & Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Daniel Cosgrove**, Space Sciences Laboratory, University of California, Berkeley, California, U.S.A.

Libration point orbits near collinear locations are inherently unstable and must be controlled. For Acceleration Reconnection and Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) Earth-Moon Lissajous orbit operations, stationkeeping is challenging because of short time scales, large orbital eccentricity of the secondary, and solar gravitational and radiation pressure perturbations. ARTEMIS is the first NASA mission continuously controlled at both Earth-Moon L_1 and L_2 locations and uses a balance of optimization, spacecraft implementation and constraints, and multi-body dynamics. Stationkeeping results are compared to pre-mission research including mode directions. [View Full Paper]

AAS 11 – 516

Strategy for Long-Term Libration Point Orbit Stationkeeping in the Earth-Moon System

Thomas A. Pavlak and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

Given the success of the first Earth-Moon libration point mission, ARTEMIS, it is likely that the Earth-Moon libration points will continue to be employed as platforms for space communications and scientific observations in the future. A long-term stationkeeping strategy for Earth-Moon libration point orbits is examined, one that does not require strict adherence to a baseline trajectory but retains the capability to meet a specific set of end-of-mission objectives for a planned lunar orbit insertion. The method is sufficiently general and is applied to both the ARTEMIS P1 and P2 trajectories in an ephemeris model. [View Full Paper]

SESSION 13: PLANETARY MISSION STUDIES
Chair: Brent Buffington
Jet Propulsion Laboratory / California Institute of Technology

AAS 11 – 517

Modeling and On-Orbit Performance Evaluation of Propellant-Free Attitude Control System for Spinning Solar Sail via Optical Parameter Switching

Ryu Funase, **Yuya Mimasu**, **Yoji Shirasawa**, **Yuichi Tsuda**, **Takanao Saiki** and **Jun'ichiro Kawaguchi**, JAXA Space Exploration Center (JSPEC), Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Yoshikazu Chishiki**, Department of Aeronautics and Astronautics, The University of Tokyo, Sagamihara, Kanagawa, Japan

A fuel-free attitude control system for a spinning solar sail which utilizes solar radiation pressure was developed. This system consists of thin-film devices attached to the sail that electrically control their optical parameters such as reflectivity, and the attitude control torque is generated by switching their optical parameters synchronizing with spin motion. Attitude control torque model for a sail of arbitrary shape and deformation was derived. The control system was implemented for Japanese interplanetary solar sail demonstration spacecraft IKAROS and the on-orbit attitude control performance was evaluated. [View Full Paper]

AAS 11 – 518

Evaluating Periodic Orbits for the JEO Mission at Europa in Terms of Lifetime and Stability

Dylan Boone and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Colorado, U.S.A.

In this work periodic orbits are differentially corrected in the Europa-centered rotating frame, including the effects of a nonspherical gravity field. The orbits found this way are then evaluated in the eccentric Europa inertial frame and their lifetime and stability are discussed. A consider covariance analysis is used to generate an error covariance matrix associated with orbiter position and velocity and science parameters. This covariance matrix is used as the basis for perturbing periodic orbits and analyzing their resulting lifetimes. The processed covariance shows that the gravitational Love number k_2 can be estimated with the required precision but the surface deformation Love number h_2 would require altimeter crossover measurements. Monte Carlo analysis is performed by scaling different components of the covariance matrix and drawing a random state perturbation vector from the associated distribution. 1000 iteration runs show that the initial Gaussian perturbations produce a non-Gaussian distribution of orbit lifetime which is skewed toward greater lifetimes. This result has positive implications for the Europa orbiter but the cause is not fully understood. Development of the square root information filter and differential corrector used are included. Histograms and lifetime statistics are referenced in the discussion. [View Full Paper]

AAS 11 – 519

Mars Sample Return: Launch and Detection Strategies for Orbital Rendezvous

Ryan C. Woolley, **Richard L. Mattingly**, **Joseph E. Riedel** and **Erick J. Sturm**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

This study sets forth conceptual mission design strategies for the ascent and rendezvous phase of the proposed NASA/ESA joint Mars Sample Return Campaign. The current notional mission architecture calls for the launch of an acquisition/caching rover in 2018, an Earth return orbiter in 2022, and a fetch rover with ascent vehicle in 2024. Strategies are presented to launch the sample into a nearly coplanar orbit with the Orbiter which would facilitate robust optical detection, orbit determination, and rendezvous. Repeating ground track orbits exist at 457 and 572 km which would provide multiple launch opportunities with similar geometries for detection and rendezvous.
[View Full Paper]

AAS 11 – 520

Mid-Course Plane-Change Trajectories Expanding Launch Windows for Mars Missions Including Venus Flyby Opportunities

Takuto Ishimatsu, **Olivier de Weck** and **Jeffrey Hoffman**, Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.

Considering future interplanetary missions to Mars from the perspective of not individual missions but a long-term spaceflight campaign, the flexibility of transportation schedule in mission planning is important. In the ΔV pork-chop plots of our past results, a two-impulse transfer trajectory generated two craters of local minima (type I and type II trajectories) and a steep mountain wall regions between the craters. Based on the fact, this paper investigates mid-course plane-change trajectories, seeking to expand launch windows for Mars missions with Venus flyby options. It is found that a mid-course plane-change trajectory has flattened out the mountain walls and expanded the launch windows. Moreover, it has also expanded the Venus flyby windows because we can choose either type of transfer for pre- and post-flyby legs. As such, mid-course plane-change trajectories offer additional opportunities for both Earth-Mars direct and Earth-Venus-Mars flyby flights, some of which are not on the Pareto front of ΔV and time of flight and others of which are. [View Full Paper]

AAS 11 – 521

Navigation Support at JPL for the JAXA Akatsuki (Planet-C) Venus Orbiter Mission

Mark S. Ryne, **Neil A. Mottinger**, **Stephen B. Broschart**, **Tung-Han You**, **Earl Higa**, **Cliff Helfrich** and **David Berry**, Mission Design & Navigation Section, Jet Propulsion Laboratory, Pasadena, California, U.S.A.

This paper details the orbit determination activities undertaken at JPL in support of the Japanese Aerospace Exploration Agency's (JAXA) Akatsuki (a.k.a. Planet-C and/or Venus Climate Orbiter) mission. The JPL navigation team's role was to provide independent navigation support as a point of comparison with the JAXA generated orbit determination solutions. Topics covered include a mission and spacecraft overview, dynamic forces modeling, cruise and approach orbit determination results, and the international teaming arrangement. Significant discussion is dedicated to the events surrounding recovery from the unsuccessful Venus orbit insertion maneuver. [View Full Paper]

AAS 11 – 522

Passive Aerogravity Assisted Trajectories for a Mars Atmospheric Sample Return Mission

Evgeniy Sklyanskiy and **Tung-Han You**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.;
Neil Cheatwood, **Alicia Dwyer Cianciolo** and **Angela Bowes**, Atmospheric Flight & Entry Systems Branch, NASA Langley Research Center, Hampton, Virginia, U.S.A.

A number of studies have demonstrated that aerodynamic lift during a planetary low-altitude atmospheric flyby can increase the V_∞ bending angle and the total ΔV achievable from gravity assist. Aero-Gravity Assist (AGA) trajectories of this type require a significantly high spacecraft L/D (lift-to-drag) ratio and a fairly robust closed-loop guidance algorithm capable of providing a desired control authority for level, nearly constant-altitude atmospheric flight. The AGA concept has been described in some previous publications as one of the techniques for Mars and Venus atmospheric sample return mission design strategies. Recent analysis has demonstrated that passive, ballistic (zero-lift) aeropass trajectories could equally satisfy potential future sample return mission objectives and provide quite robust and simple alternatives to a complex guided AGA lifting trajectory design. [View Full Paper]

AAS 11 – 523

Plan and Progress for Updating the Models Used for Orbiter Lifetime Analysis

Mark A. Vincent, Navigation & Mission Design, Raytheon, Pasadena, California, U.S.A.; **Todd A. Ely** and **Theodore H. Sweetser**, Mission Design & Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena California, U.S.A.

Mars orbiting spacecraft such as MGS and Odyssey have successfully used probabilistic predictions of extended orbital lifetimes to satisfy planetary protection requirements. The methodology used to find the necessary initial orbit altitudes was based upon a simplified atmosphere model (MARS01) and a new technique (the "Trinomial Method") for determining the probabilistic values. Recently obtained measurements of the parameters representing the Mars atmosphere indicate that analysis should be performed to determine if MARS01 should be adjusted. To further improve the efficiency of the Trinomial Method, it is also proposed to automate some of the trial-and-error steps in the process. By improving the efficiency of the algorithms some of the conservatism in the results can be removed which would benefit satellite operations. Another recent discovery is that there are significant effects during the propagation of Mean elements from resonances in the higher order gravity field terms. Developing and implementing algorithms to properly account for these resonances is being proposed. Doing so will determine the relationship between resonances and orbital lifetimes and enable the continued benefit derived from the Mean element's efficient propagation speed that is necessary to do lifetime studies in a timely manner. As a separate analysis, the parameters in the Earth-equivalent of MARS01 are being re-evaluated and implemented into the new suite of JPL software. [View Full Paper]

AAS 11 – 524

Selection of Mercury's Surface Features Coordinates for the BepiColombo Rotation Experiment

Alessandra Palli and **Paolo Tortora**, Seconda Facoltà di Ingegneria, Università di Bologna, Forlì (FC), Italy

Among the scientific objectives addressed by the Radio Science Experiment hosted on board the ESA mission BepiColombo is the retrieval of the rotational state of planet Mercury. In fact, the estimation of the obliquity and the librations amplitude were proven to be fundamental for constraining the interior composition of Mercury. This is accomplished by the Mercury Orbiter Radio science Experiment via a strict interaction among different payloads thus making the experiment particularly challenging.

The underlying idea consists in capturing images of the same landmark on the surface of the planet in different epochs in order to observe a displacement of the identified features with respect to a nominal rotation which allows to estimate the rotational parameters. Observations must be planned accurately in order to obtain image pairs carrying the highest information content for the following estimation process. This is not a trivial task especially in light of the several constraints involved. First of all, the peculiar Mercury's dynamic characterized by a 3:2 spin orbit resonance and the dependence of librations amplitude on Mercury's mean anomaly leads to the fact that under the same illumination conditions no libration is observed. Another delicate issue is represented by the pattern matching process between image pairs for which the lowest correlation errors are desired. Although modern algorithms are able to reach sub-pixels accuracies, different strategies must be implemented according to the type of images to be matched, especially for what concerns illumination and scale variations, and the type of features to be detected.

Due to the many physical and operational constraints involved in this complex experiment, an end-to-end simulator of the experiment was designed with the final objective of establishing the optimal observations planning. In particular, this paper will focus on the software implemented for the generation of a map and database of the global observations, and on postprocessing simulations fundamental to lead the image pairs selection process. [View Full Paper]

AAS 11 – 525

(Paper Withdrawn)

AAS 11 – 526

Stationkeeping Strategy for Laplace-JGO Science Phase around Ganymede

Mirjam Boere and **Arnaud Boutonnet**, Mission Analysis, ESA ESOC, Darmstadt, Germany

The ESA Jupiter Ganymede Orbiter mission envisages a spacecraft in low altitude polar orbit around Ganymede. Due to the combined effect of Ganymede's gravity potential and Jupiter's attraction, an initially circular orbit rapidly becomes eccentric. A method analytically combining the effect of Jupiter's attraction and all zonal terms of the gravity potential is presented in this paper. It allows finding an unstable equilibrium point around which stationkeeping is performed. Numerical integration, including the full gravity potential, orbit determination and maneuvers uncertainties, validates the approach. Frequency of maneuvers and deltaV cost are assessed in the frame for the JGO. [View Full Paper]

SESSION 14: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

Chair: Dr. Yanping Guo
Johns Hopkins University Applied Physics Laboratory

AAS 11 – 527

A General Event Location Algorithm with Applications to Eclipse and Station Line-of-Sight

Joel J. K. Parker and **Steven P. Hughes**, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

A general-purpose algorithm for the detection and location of orbital events is developed. The proposed algorithm reduces the problem to a global root-finding problem by mapping events of interest (such as eclipses, station access events, etc.) to continuous, differentiable event functions. A stepping algorithm and a bracketing algorithm are used to detect and locate the roots. Examples of event functions and the stepping/bracketing algorithms are discussed, along with results indicating performance and accuracy in comparison to commercial tools across a variety of trajectories. [View Full Paper]

AAS 11 – 528

Cassini Solstice Mission Maneuver Experience: Year One

Sean V. Wagner, **Juan Arrieta**, **Christopher G. Ballard**, **Yungsun Hahn**, **Paul W. Stumpf** and **Powtawche N. Valerino**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Cassini-Huygens spacecraft began its four-year Prime Mission to study Saturn's system in July 2004. Two tour extensions followed: a two-year Equinox Mission beginning in July 2008 and a seven-year Solstice Mission starting in September 2010. This paper highlights Cassini maneuver activities from June 2010 through June 2011, covering the transition from the Equinox to Solstice Mission. This interval included 38 scheduled maneuvers, eight targeted Titan flybys, three targeted Enceladus flybys, and one close Rhea flyby. In addition, beyond the demanding nominal navigation schedule, numerous unforeseen challenges further complicated maneuver operations. These challenges will be discussed in detail. [View Full Paper]

AAS 11 – 529

Earth Orientation Parameter Considerations for Precise Spacecraft Operations

Ben K. Bradley, **Aurore Sibois** and **Penina Axelrad**, Aerospace Engineering Sciences Dept., University of Colorado at Boulder, Colorado, U.S.A.; **David A. Vallado**, Analytical Graphics Inc., Center for Space Standards and Innovation, Colorado Springs, Colorado, U.S.A.

Earth orientation parameters (EOP) are crucial for correctly converting between the Geocentric Celestial Reference Frame (GCRF) and International Terrestrial Reference Frame (ITRF), affecting parameters such as station coordinates, satellite positions, and non-spherical gravitational acceleration vectors. EOP interpolation methods and ocean tide corrections are shown to have a notable impact on these precise frame transformations. This paper investigates the accuracies and speeds of available methods that should be considered when using EOPs, allowing satellite operators and astrodynamicists to make informed decisions when choosing the best implementation for their individual needs. [View Full Paper]

AAS 11 – 530

Flight Path Control Design for the Cassini Solstice Mission

Christopher G. Ballard and **Rodica Ionasescu**, Cassini Navigation Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Cassini spacecraft has been in orbit around Saturn for just over 7 years, with a planned 7-year extension, called the Solstice Mission, which started on September 27, 2010. The Solstice Mission includes 205 maneuvers and 70 flybys which consist of the moons Titan, Enceladus, Dione, and Rhea. This mission is designed to use all available propellant with a statistical margin averaging 0.6 m/s per encounter, and the work done to prove and ensure the viability of this margin is highlighted in this paper.
[View Full Paper]

AAS 11 – 531

Guidance Algorithms for Asteroid Intercept Missions with Precision Targeting Requirements

Matt Hawkins, **Yanning Guo** and **Bong Wie**, Asteroid Deflection Research Center, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

Rendezvous and intercept missions to smaller asteroids require precision guidance and control in the terminal mission phase. The zero-effort-miss (ZEM) and zero-effort-velocity (ZEV) information are used to formulate autonomous feedback guidance laws. A terminal-phase guidance strategy for a variety of intercept missions is developed. Different types of navigation information are assumed to be available from different spacecraft configurations and hardware choices. Guidance laws are developed for different mission configuration options. Guidance laws for both rendezvous and impact are studied. Optimal feedback guidance laws are also investigated for asteroid intercept/rendezvous missions. Simulations show the effectiveness of the various guidance laws. [View Full Paper]

AAS 11 – 532

Guidance and Navigation Linear Covariance Analysis for Lunar Powered Decent

Travis J. Moesser, ATK, Promontory, Utah, U.S.A.;
David K. Geller and **Shane Robinson**, Department of Mechanical and Aerospace Engineering, Utah State University, Logan, Utah, U.S.A.

A linear covariance analysis is conducted to assess closed-loop guidance, navigation, and control system (GN&C) performance of the Altair vehicle during lunar powered descent. Guidance algorithms designed for lunar landing are presented and incorporated into the closed-loop covariance equations. Navigation-based event triggering is also included in the covariance formulation to trigger maneuvers and control dispersions. Several navigation and guidance trade studies are presented demonstrating the influence of triggering and guidance and study parameters on the vehicle GN&C performance. [View Full Paper]

AAS 11 – 533

Low-Thrust Adaptive Guidance Scheme Accounting for Engine Performance Degradation

Iman Alizadeh, **Solmaz Sajjadi-Kia** and **Benjamin Villac**, University of California, Irvine, California, U.S.A.

An adaptive low-thrust guidance scheme is presented based on combination of Modified-Gain Extended Kalman Filter (MGEKF) and Extended Linear Quadratic Gaussian (ELQG) controller. The benefit of the proposed method is that the unknown parameters of the system are estimated on-line and their estimates are directly incorporated in designing the control law. The algorithm is shown to be capable of handling large perturbations from the nominal performance in the presence of measurement and process noise. The method is applied to the problem of low-thrust spacecraft guidance subject to engine performance degradation in unstable orbital environments. It is shown that the proposed guidance scheme can indeed compensate for the large changes in the engine operating conditions. [View Full Paper]

AAS 11 – 534

Preliminary Analysis for the Navigation of Multiple-Satellite-Aided Capture Sequences at Jupiter

Alfred E. Lynam and **James M. Longuski**, School of Aeronautics & Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

Multiple-satellite-aided capture employing gravity assists of more than one Galilean moon can help capture a spacecraft into orbit about Jupiter. Each additional moon flyby reduces the propulsive ΔV required for Jupiter capture. While the existence of these trajectories has been demonstrated deterministically, the challenges associated with actually navigating a spacecraft through several close flybys in rapid succession are nontrivial. This paper addresses these navigation challenges by using simulated observations to estimate a spacecraft's orbit as it approaches Jupiter and by targeting trajectory correction maneuvers to guide the spacecraft through multiple-satellite-aided capture sequences. Results indicate that radiometric navigation alone can easily provide safe double-satellite-aided capture sequences using a ballistic strategy, i.e. without any trajectory correction maneuvers (TCMs) in between flybys. However, triple-satellite-aided capture sequences require the operational capacity to target TCMs in between flybys in order to be feasible. [View Full Paper]

AAS 11 – 535

Radar Altimetry and Velocimetry for Inertial Navigation: A Lunar Landing Example

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The traditional role that altimetry and velocimetry have played in spacecraft landings is to provide a direct measure of the spacecraft's surface altitude and surface relative velocity; however, their role in determining an inertial position and velocity has seen limited investigation. In this study, inertially sensitive measurement models for altimetry and velocimetry are formulated and include relevant instrument and environment error models. These models are applied and simulated for a realistic lunar landing scenario that is based on recent work for NASA's Altair lander. The preliminary results indicate that an inertial landing accuracy of several meters is possible.
[View Full Paper]

AAS 11 – 536

Variable State Size Optimization Problems in Astrodynamics: *N*-Impulse Orbital Maneuvers

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This paper details recent results in variable state size optimization problems in astrodynamics. The application presented in this paper is fuel-optimal N-impulse orbital maneuvers. Previous work required the user to choose the number of impulses, N, while the current work considers N as a variable to be optimized, making the state size a variable throughout the optimization process. It is well known that for $N > 2$, a numerical optimization method is required for a general solution to the orbit transfer problem. Two algorithmic approaches are presented such that they may be used with a variety of numerical optimization techniques. The first structure runs an outer problem which optimizes the number of impulses, thus determining the length of the state vector, while an inner problem optimizes the orbital maneuver for the given number of impulses. The second structure incorporates the variable N into the state vector to be optimized, leading to a dynamic state vector length. This structure causes some properties of any given numerical optimization method to necessarily be modified. For example, the evolutionary operators must be able to deal with states of different lengths. Examples are provided that show new scenarios under each structure and show agreement with examples from the literature. [View Full Paper]

AAS 11 – 537

(Paper Withdrawn)

SESSION 15: SATELLITE CONSTELLATIONS
Chair: Dr. Ossama Abdelkhalik, Michigan Technological University

AAS 11 – 538
Constellation Design for Space-Based Situational Awareness Applications: An Analytical Approach

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Optimization processes rely on the availability of a pre-defined cost function. Generally, such representations are often analytically available. However, when considering optimal constellation design for space-based space situational awareness applications, a closed-form representation of the cost index is only available under certain assumptions. The present investigation focuses on a subset of cases that admit exact representations. In this case, geometrical arguments are employed to establish an analytical formulation for the coverage area provided as well as for the coverage multiplicity. These analytical results are essential in validating numerical approximations that are able to simulate more complex configurations. [View Full Paper]

AAS 11 – 539
Coverage Analysis of Specified Area for an Agile Earth Observation Satellite

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The agile Earth observation satellite is a new generation of remote sensing satellite with high ability of attitude maneuver in the observing activities. Coverage analysis is an essential but difficult problem in mission design, plan and scheduling. In this paper, the observing mode of an agile satellite was defined by its attitude movement, and different geometry models of coverage analysis were discussed for different observing modes in low earth orbit (LEO). According to the capability feature of on-board instruments, a method of specified area projection transformation and dynamic decomposition was proposed. Finally, the simulation method based on projection and decomposition was presented for analyzing the coverage problem. [View Full Paper]

AAS 11 – 540

Deriving Global Time-Variable Gravity from Precise Orbits of the Iridium NEXT Constellation

B. C. Gunter, **J. Encarnação**, **P. Ditmar**, **R. Klees**, **P. W. L. van Barneveld** and **P. Visser**, Delft Institute of Earth Observation and Space Systems (DEOS), Delft University of Technology, Delft, The Netherlands

The goal of this study is to help define the precise positioning requirements needed to observe time-variable gravity with the upcoming Iridium NEXT satellite constellation. Various sources of orbit error that might be expected for the Iridium NEXT satellites are discussed, and a simulation study exploring the impact of these errors on the expected accuracy and resolution of the gravity field models is presented. An additional scenario is also investigated highlighting the improvement in accuracy that could be realized if simple intersatellite range measurements could be obtained using the Iridium NEXT communication network. Finally, a limited study into the FORMOSAT-3/COSMIC data is conducted to assess the realistic performance of kinematic orbit positioning techniques using receivers in a similar mission scenario. [View Full Paper]

AAS 11 – 541

Estimation of Atmospheric and Ionospheric Effects in Multi-Satellite Orbit Determination Using Crosslinks

Joanna C. Hinks and **Mark L. Psiaki**, Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York

A method is proposed for determining the orbits of multiple satellites in the same orbital plane by employing both downlink and crosslink radio-navigation signals. Such an orbit determination scheme must account for orbit perturbations due to unpredictable atmospheric drag and for ionospheric delay effects on single-frequency crosslink ranging measurements. The proposed method can improve orbit accuracy and sense variations in the space environment by simultaneously estimating satellite orbits and density distributions for the atmosphere and ionosphere. Satellites in the same orbital plane encounter roughly the same density features after a time delay corresponding to orbital separation, and this implies that errors due to both atmospheric drag and ionospheric delay will be spatially correlated. By exploiting rather than ignoring this correlation, it is hoped that orbit improvements associated with a given satellite will also benefit the orbit estimates for other satellites in the same plane. A linearized observability analysis indicates that the proposed estimation system is observable without *a priori* information. A generalized consider covariance analysis shows that estimating atmospheric and ionospheric density rather than applying standard models significantly improves orbit determination accuracy. [View Full Paper]

AAS 11 – 542

Numerical Continuation of Optimal Spacecraft Placements for LiAISON Constellations

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An anticipated need for continuing space exploration is space-based infrastructure that provides navigation and communications support to space traffic in the larger cislunar region. This study leverages previous work that establishes the methodology for selecting candidate orbits and determining optimal satellite configurations for LiAISON constellations. While previous work provided pointwise analyses, this study presents algorithms to efficiently extend solutions over larger design spaces by employing numerical continuation techniques to circumvent computational bottlenecks. Results from two case studies are presented for the LL1 halo and axial periodic orbit families in the restricted Earth-Moon system. [View Full Paper]

AAS 11 – 543

Optimal Constellation Design for Space Based Situational Awareness Applications

A. T. Takano and **B. G. Marchand**, Department of Aerospace Engineering, University of Texas, Austin, Texas, U.S.A.

Modern space situational awareness is focused on the detection, tracking, identification, and characterization of passive and active resident space objects. In the past, this process relied primarily on ground-based sensors. However, difficulties arise when smaller objects are considered, in the nano- or pico-satellite range for instance. To supplement ground sensing capabilities, a constellation of space based sensors is envisioned. In this study, concepts from computer graphics and numerical optimization are fused into a unique constellation design approach for space based space situational awareness applications. [View Full Paper]

AAS 11 – 544

Strategy for Mitigating Collisions between Landsat-5 and the Afternoon Constellation

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The NASA Goddard Space Flight Center Earth Science Mission Operations project, the French space agency Centre National d'Études Spatiales, the Argentinian space agency Comisión Nacional de Actividades Espaciales, and the United States Geological Survey all operate spacecraft in sun-synchronous frozen orbits. The orbits are planned to not place any of the spacecraft at risk of colliding with another. However, evolution of these orbits over time has compromised the safe interaction between Landsat-5 and the Afternoon Constellation. This paper analyzes the interactions between the Landsat-5 spacecraft and the Afternoon Constellation members over a period of 6 years, describing the current risk and plan to mitigate collisions in the future. [View Full Paper]

AAS 11 – 545

The Implementation of MPI in the Autonomous Navigation of Constellation

Xiaofang Zhao, **Shenggang Liu** and **Chao Han**, School of Astronautics, Beihang University, Beijing, China

The autonomous navigation of constellation can be decoupled into the autonomous orbit determination (AOD) and autonomous time synchronization (ATS) through dual directional range measurements. In the AOD process, the spherical simplex sigma point filter is used to estimation the orbit s' state. Meanwhile, the Kalman filter is implemented in the ATS process to estimate the sate of onboard atom clock. The computation procedure is of complexity, huge burden of computation and low speed of calculation. In accordance with this character of the navigation process, the messaging passing interface is inducted to this process to parallelize the AOD and ATS of the constellation. The crucial stages of the navigation are simulated using MPI and the parallel speedup and parallel efficiency are given to evaluate the algorithm performance. Simulation results show that this parallel program speedups the computation and make the computation time much shorter. Moreover, it is hopeful to use MPI to parallel the navigation algorithm to make the simulation more efficient and time saving when the constellation gets more members. [View Full Paper]

SESSION 16: SPECIAL TOPIC: MESSENGER AT MERCURY

Chairs: Mr. James McAdams,
Johns Hopkins University / Applied Physics Laboratory
Mr. Kenneth Williams, KinetX, Inc.

AAS 11 – 546

MESSENGER – Six Primary Maneuvers, Six Planetary Flybys, and 6.6 Years to Mercury Orbit

James V. McAdams, **Dawn P. Moessner** and **Daniel J. O'Shaughnessy**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.;
Kenneth E. Williams, **Anthony H. Taylor** and **Brian R. Page**, KinetX, Inc., Space Navigation and Flight Dynamics Practice, Simi Valley, California, U.S.A.

On 18 March 2011, the MErcury Surface, Space ENvironment, Geochemistry, and Ranging (MESSENGER) spacecraft became the first probe to orbit Mercury. The spacecraft's 6.6-year journey to Mercury orbit included six large trajectory-correction maneuvers and six planetary flybys. These planetary gravity assists imparted the vast majority of velocity change required to transform the spacecraft trajectory from Earth orbit departure to Mercury arrival. This paper summarizes the design and performance of all planetary flybys and course-correction maneuvers through orbit insertion, as well as the results of targeting the planetary-flyby aim points using the acceleration on the spacecraft imparted by solar radiation pressure. [View Full Paper]

AAS 11 – 547

The MESSENGER Spacecraft's Orbit-Phase Trajectory

Dawn P. Moessner and **James V. McAdams**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

After MESSENGER's 18 March 2011 Mercury orbit insertion (MOI), the spacecraft began its year-long primary science mission. Trajectory perturbations from solar gravity, Mercury's gravity field, and solar radiation pressure shift orbit periapsis higher in altitude and Mercury latitude during the primary mission. Five orbit-correction maneuvers (OCMs) will either lower periapsis altitude or increase orbit period. After the primary mission, MESSENGER will either drift until impacting Mercury or begin an extended mission. Extended mission options require OCMs to establish and maintain a new orbit. Final results for MOI and OCM-1 indicate a successful start to the primary mission. [View Full Paper]

AAS 11 – 548

Achievable Force Model Accuracies for MESSENGER in Mercury Orbit

Dale R. Stanbridge, **Kenneth E. Williams**, **Anthony H. Taylor**, **Brian R. Page**, **Christopher G. Bryan**, **David W. Dunham**, **Peter Wolff** and **Bobby G. Williams**, KinetX, Inc., Space Navigation and Flight Dynamics Practice, Simi Valley, California, U.S.A.; **James V. McAdams** and **Dawn P. Moessner**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is the seventh mission in NASA's Discovery Program. The spacecraft, launched from Cape Canaveral Air Force Station in August 2004, arrived in orbit about Mercury in March 2011 to begin a one-year scientific investigation. While in orbit, the spacecraft is subject to a variety of forces, including Mercury and solar gravity, solar and planetary radiation effects, and propulsive events associated with orbit correction and momentum desaturation. This paper describes the challenges for navigation in terms of achieving the highest accuracy possible for relevant force models to support orbit determination and reconstruction over the Mercury orbital phase of the MESSENGER mission. [View Full Paper]

AAS 11 – 549

Applying Experience from Mercury Encounters to MESSENGER's Mercury Orbital Mission

Brian R. Page, **Kenneth E. Williams**, **Anthony H. Taylor**, **Dale R. Stanbridge**, **Christopher G. Bryan**, **Peter J. Wolff** and **Bobby G. Williams**, KinetX, Inc., Space Navigation and Flight Dynamics Practice, Simi Valley, California, U.S.A.;
Daniel J. O'Shaughnessy and **Sarah H. Flanigan**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is the seventh in NASA's Discovery Program series. The spacecraft was launched in August 2004 and began an interplanetary cruise that culminated in insertion into orbit about Mercury in March 2011 for a nominal one-year scientific investigation. The cruise phase included six planetary gravity-assist flybys and eighteen propulsive events, which included five large deep-space maneuvers, one in two parts, and twelve smaller trajectory-correction burns. From the approach to the first Mercury flyby through orbital insertion about the innermost planet, an interval that spanned over three years, solar sailing was employed successfully for trajectory correction. This paper describes the navigation performance achieved for the three Mercury flybys and how experiences gained during the mission cruise phase have been applied to support Mercury orbit insertion and maintenance operations during the Mercury orbital phase of the MESSENGER mission. [View Full Paper]

AAS 11 – 550

Guidance and Control of the MESSENGER Spacecraft in the Mercury Orbital Environment

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The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft faces a demanding environment while in orbit about Mercury. During the one-year-long primary orbital mission phase, the guidance and control subsystem faces challenging constraints, most of which were not encountered during the cruise phase, and must incorporate the planning and approval of each weeklong command sequence within only a three-week period. This paper details the analyses that were performed to develop a streamlined and effective methodology for adhering to orbital constraints. The methodology, which has proven effective in ensuring spacecraft health and safety while in orbit about Mercury, is detailed. [View Full Paper]

AAS 11 – 551

MESSENGER Spacecraft Pointing Performance during the Mission's Mercury Orbital Phase

Robin M. Vaughan, **Daniel J. O'Shaughnessy** and **Sarah H. Flanigan**,
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A number of attitude changes are executed daily by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft in orbit about Mercury to collect and return science measurements to Earth. Prior to orbit insertion in March 2011, several analyses verified that the guidance and control system is capable of executing the orbital attitude profiles within the required accuracy. This paper compares the desired attitude profiles with profiles obtained from ground simulations and with attitude telemetry from a selected week in orbit in May 2011. The ground software tools are shown to match each other and actual spacecraft attitude to within a few tenths of a degree, which is sufficient for science planning purposes. Attitude changes introduced by spacecraft ephemeris model updates and time biasing of attitude and instrument commands in each sequence load are shown to maintain the intended planet-relative geometry without introducing large deviations in turn durations or causing violations of attitude constraints. These analyses provide confidence that the ground simulations performed throughout the orbit sequence development process are adequate to ensure safe execution of the sequences by the spacecraft. [View Full Paper]

AAS 11 – 552

Modeling the Effects of Albedo and Infrared Radiation Pressures on the MESSENGER Spacecraft

Christopher J. Scott, **James V. McAdams**, **Dawn P. Moessner** and **Carl J. Ercol**,
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While the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is in orbit about Mercury, the navigation team will refine a spherical-harmonic gravity-field model that requires accurate estimation of all perturbing accelerations, including those induced by Mercury's surface albedo and infrared radiation. The incident flux on each spacecraft surface is estimated and converted into perturbing accelerations, which are then incorporated into a propagation model within the Satellite Tool Kit Astrogator module. This paper outlines the calculation and predicted effects of these perturbing accelerations on the MESSENGER spacecraft throughout the mission's orbital phase. [View Full Paper]

SESSION 17: TRAJECTORY OPTIMIZATION II
Chair: Dr. Chris Ranieri, The Aerospace Corporation

AAS 11 – 452

Ephemeris Model Optimization of Lunar Orbit Insertion from a Free Return Trajectory

Mark Jesick and **Cesar Ocampo**, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, W. R. Woolrich Laboratories, Austin, Texas, U.S.A.

With the discovery of water ice at the moon's south pole, future human lunar exploration will likely occur at polar sites and, therefore, require high inclination orbits. This work details an automated architecture for constructing minimum-fuel lunar orbit insertion sequences while ensuring crew safety by maintaining a ballistic Earth return trajectory, which is free to vary during optimization. The Jacobian of the constraints is derived analytically to eliminate the need for finite difference approximations; where necessary, gradients are determined with linear perturbation theory. An impulsive engine model is used before conversion to a finite thrust model. [View Full Paper]

AAS 11 – 553

2011 Mars Science Laboratory Launch Period Design

Fernando Abilleira, Inner Planets Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Mars Science Laboratory mission, set to launch in the fall of 2011, has the primary objective of landing the most advanced rover to date to the surface of Mars to assess whether Mars ever was, or still is today, able to sustain carbon-based life. Arriving at Mars in August 2012, the Mars Science Laboratory will also demonstrate the ability to deliver large payloads to the surface of Mars, land more accurately (than previous missions) in a 20-km by 25-km ellipse, and traverse up to 20 km. Following guided entry and parachute deployment, the spacecraft will descend on a parachute and a Powered Descent Vehicle to safely land the rover on the surface of Mars. The launch/arrival strategy is driven by several key requirements, which include: launch vehicle capability, atmosphere-relative entry speed, communications coverage during Entry, Descent and Landing, latitude accessibility, and dust storm season avoidance. Notable among these requirements is maintaining a telecommunications link from atmospheric entry to landing plus one minute, via a Direct-To-Earth X-band link and via orbital assets using an UHF link, to ensure that any failure during Entry, Descent and Landing can be reconstructed in case of a mission anomaly. Due to concerns related to the lifetime of the relay orbiters, two additional launch/arrival strategies have been developed to improve Entry, Descent, and Landing communications. This paper discusses the final launch/arrival strategy selected prior to the launch period down-selection that is scheduled to occur in August 2011. It is also important to note that this paper is an update to Ref. 1 in that it includes two new Type 1 launch periods and drops the Type 2 launch period that is no longer considered. [View Full Paper]

AAS 11 – 554
(Paper Withdrawn)

AAS 11 – 555

Approximation of Constraint Low-Thrust Space Trajectories Using Fourier Series

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Finite Fourier series is implemented for rapid low-thrust rendezvous trajectory approximation, in the presence of thrust acceleration constraints. The new representation along with the constraint handling capability makes this method suitable for low-thrust trajectory feasibility assessments, which is crucial in the preliminary phase of mission planning. In addition, the resulting solutions are good initial guesses for direct optimization techniques. Few case studies are presented: simple Earth-Mars rendezvous, LEO-to-GEO rendezvous, orbit raising, and two phasing problems. Results, clearly depict the advantage of this method as a general method applicable to a wide range of problems. [View Full Paper]

AAS 11 – 556

Closed-Form and Numerically-Stable Solutions to Problems Related to the Optimal Two-Impulse Transfer between Specified Terminal States of Keplerian Orbits

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The first part of the paper presents some closed-form solutions to the optimal two-impulse transfer between fixed position and velocity vectors on Keplerian orbits when some constraints are imposed on the magnitude of the initial and final impulses. Additionally, a numerically-stable gradient-free algorithm with guaranteed convergence is presented for the minimum delta-v two-impulse transfer. In the second part of the paper, cooperative bargaining theory is used to solve some two-impulse transfer problems when the initial and final impulses are carried by different vehicles or when the goal is to minimize the delta-v and the time-of-flight at the same time. [View Full Paper]

AAS 11 – 557

Coast Arcs in Optimal Multiburn Orbital Transfers

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The determination of the durations of the coast arcs in optimal finite-thrust, multiple-burn orbital transfer problems is investigated in detail in this paper. The structure of the zeros of the switching function which dictates when to switch from a coast to the next burn is thoroughly analyzed under 3 different ways of treating the gravity in the costate equations. Unlike existing approaches which rely on brute-force or relatively crude numerical searches for the correct switching time and suffer from potential failures, this paper shows that the correct zero of the switching function, with each of the gravity modeling, can either be obtained in closed form, or determined accurately and rapidly in a fail-safe way by solving a polynomial of at most degree 5. Numerical examples provide clear comparison of the results and show how when other methods fail, the proposed approach still ensures the correct solution. [View Full Paper]

AAS 11 – 558

Implicit Solution for the Low–Thrust Lambert Problem by Means of a Perturbative Expansion of Equinoctial Elements

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A method for solving the so called low–thrust Lambert's problem is proposed. After formulating it as a two-point boundary value problem, where initial and final positions are provided in terms of equinoctial variables, a first-order perturbative approach is used for investigating the variation of orbital elements generated by the low–thrust propulsion system, which acts as a perturbing parameter with respect to the zero-order Keplerian motion. An implicit formulation is thus obtained which allows for the determination of the low–thrust transfer trajectory driving the equinoctial parameters from the initial to their final values in a prescribed time. Three test cases are presented, which demonstrate the flexibility of the method for different missions: (i) an interplanetary transfer from Earth to Mars, (ii) a spiral multi-revolution transfer from low Earth orbit to the International Space Station, and (iii) a geostationary transfer orbit to a geostationary orbit. [View Full Paper]

AAS 11 – 559

Optimization of Stable Multi-Impulse Transfers

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This paper addresses the optimization of stable multi-impulse transfers. These transfers allow a spacecraft to coast near families of stable periodic orbits while staying within the associated stability region. They result in fail-safe transfers with respect to a misguided thrust and may provide an interesting strategy for human missions to small bodies. The optimization problem considered consists of the minimization of sequences of small impulses transferring a spacecraft between two given periodic orbits along a stable family under path and impulse constraints to stay within the stability region. A two-level optimization strategy is proposed that results in locally optimal transfers. An "inner" optimization solves the problem of minimum fuel direct transfer between two nearby orbits while an "outer" optimization solves the problem for the optimal selection of the series of intermediate orbits. Simple cases where (semi-) analytic solutions are available (such as Hohmann and minimum impulse Lambert's transfers), the (semi-) analytic solutions have been used to validate the proposed strategy and investigate the issue of global optimality. The proposed method is also illustrated for a case of a transfer along distant retrograde orbits in the restricted three-body problem. This case indeed represents a large class of stable capture routes to low altitude orbits in various systems.
[View Full Paper]

AAS 11 – 560

Trajectory Optimization Employing Direct Implicit Integration of 2nd Order Dynamical Systems and Non-Linear Programming

Stephen W. Paris, Boeing Research & Technology, Seattle, Washington, U.S.A.

Typically numerical solutions of 2nd order dynamical systems are accomplished by transforming the 2nd order dynamics into an equivalent 1st order system. Implicit integration can allow for efficient direct solution of 2nd order dynamical systems. This combined with nonlinear programming provides an efficient technique for trajectory optimization. Compact schemes based on implicit integration for solving optimal trajectory problems based on 1st and order 2nd dynamical systems are presented. Computation experiences are given for applying and comparing these trajectory optimization methods to aerospace problems. The results demonstrate that significant computational efficiencies can be realized if the native 2nd order dynamical system is solved directly.
[View Full Paper]

AAS 11 – 561

(Paper Withdrawn)

AAS 11 – 562

Low-Thrust Control of Lunar Orbits

Nathan Harl and **Henry J. Pernicka**, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.

In this paper, a technique for stationkeeping low-altitude lunar orbits using continuous low-thrust systems is presented. The method involves the use of a general performance index, which is designed to minimize the difference between the instantaneous orbital elements of a spacecraft and some desired set of orbital elements. Due to the generality of the controller design, the resultant controller can be applied to a variety of mission scenarios about various bodies in space. To minimize the designed performance index, a Sequential Quadratic Programming algorithm is used. The primary application of the general controller design in this study is the problem of generating and maintaining low-altitude, polar, Sun-synchronous orbits about the Moon. Such orbits are useful for lunar mapping missions, such as with NASA's Lunar Reconnaissance Orbiter (LRO) mission which began in June of 2009. Results are presented demonstrating that lunar Sunsynchronous orbits can be maintained for extended durations of time with constant low-thrust levels, even in the presence of eclipse effects. [View Full Paper]

AAS 11 – 612

Taylor Series Trajectory Calculations Including Oblateness Effects and Variable Atmospheric Density

James R. Scott, NASA Glenn Research Center, Systems Engineering and Analysis Division, Cleveland, Ohio, U.S.A.

Taylor series integration is implemented in NASA Glenn's Spacecraft N-body Analysis Program, and compared head-to-head with the code's existing 8th-order Runge-Kutta Fehlberg time integration scheme. This paper focuses on trajectory problems that include oblateness and/or variable atmospheric density. Taylor series is shown to be significantly faster and more accurate for oblateness problems up through a 4x4 field, with speedups ranging from a factor of 2 to 13. For problems with variable atmospheric density, speedups average 24 for atmospheric density alone, and average 1.6 to 8.2 when density and oblateness are combined. [View Full Paper]

SESSION 18: ATTITUDE D&C I
Chair: Dr. Don Mackison, University of Colorado

AAS 11 – 563

Attitude Motion of Spacecraft with Geometrically Distributed Multiple Liquid Stores

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In this paper we develop vectorial equations of motion of a spacecraft which is equipped with multiple thrusters, control wheels, and liquid propellant storages. As equivalent mechanical models to describe the slosh motion of liquid in tanks, spherical pendulum models are adopted. Newton-Euler method is used to formulate full nonlinear equations of motion for a rigid-spacecraft with two propellant tanks and numerical simulations are conducted under the restricted conditions in order to check the appropriateness of the derived models. [View Full Paper]

AAS 11 – 564

Attitude Propagation for a Slewing Angular Rate Vector with Time Varying Slew Rate

Russell P. Patera, The Aerospace Corporation, El Segundo, California, U.S.A.

An earlier work found that vehicle attitude propagation accuracy is improved by solving the problem in a reference frame that slews at a constant rate with respect to the vehicle frame. The method is effective because the angular rate of the slewing frame changes direction at a slower rate than does the angular rate of the vehicle frame. This work extends the method by introducing two or more slewing reference frames that further increase attitude propagation accuracy. The method is further enhanced by using slewing frames that have time dependent rather than constant slew rates. This enhancement is used to derive the analytical solution to pure coning motion with time dependent coning frequency. The method is applicable to dynamic simulations and strapdown inertial navigation units used on aerospace vehicles that output angular rate vectors. Several numerical examples are presented. [View Full Paper]

AAS 11 – 565

Automatic Mass Balancing for Small Three-Axis Spacecraft Simulator Using Sliding Masses Only

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Small satellite spacecraft simulator is a very useful tool for developing, improving and verifying spacecraft attitude control algorithms. Accurate ground testing of spacecraft attitude dynamics and control requires a frictionless and space-like environment that can be simulated using spherical air bearing. The major issue using spherical air bearing is the minimization of the gravitational torque due to misalignment between the spacecraft center of mass and center of rotation. This paper introduces a novel automatic mass balancing technique that allows to drastically reduce the gravitational torque by a precise alignment of the center of mass and the center of rotation using sliding masses only. The automatic mass balancing method, is based on an adaptive dynamical nonlinear feedback control law that relocates, in real-time, the center of mass into the spacecraft simulator center of rotation. The control law derivation and simulation are performed, based on real parameters of CubeSat three-axis simulator of the Spacecraft Robotic and NanoSatellite Laboratory at the Naval Postgraduate School.
[View Full Paper]

AAS 11 – 566

Evaluating the Stability Robustness to Model Errors of Multiple-Period Repetitive Control

Edwin S. Ahn and **Richard W. Longman**, Department of Mechanical Engineering, Columbia University, New York, New York, U.S.A.; **Jae J. Kim**, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California, U.S.A.

Spacecraft often have multiple rotating parts such as CMG's, reaction wheels, or a momentum wheel. Slight imbalance within any of these devices will cause vibration of the spacecraft structure that can impair the functioning of fine pointing equipment. Repetitive control (RC) is a candidate for active vibration isolation of such equipment, and has the advantage that in theory it is capable of completely canceling the effects of such disturbances. For RC that addresses a single period, the bounds for robustness to model error are known and simple. To address these spacecraft problems, a previous study developed improved RC design methods to handle multiple unrelated disturbance periods. It is the purpose of this paper to study how addressing multiple unrelated periods in RC influences the stability robustness to model error. Multiple period analogs of single period stability conditions are developed. The complexity of stability tests is significantly increased, and it is shown that stability robustness deteriorates significantly as one introduces additional periods. [View Full Paper]

AAS 11 – 567

Nonlinear Control Analysis of a Double-Gimbal Variable-Speed Control Moment Gyro

Daan Stevenson and **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

A single Double-Gimbal Variable-speed control moment gyro (DGV) is considered as a method for three-dimensional spacecraft attitude control. First, the system's equations of motion are developed, where gimbal and wheel accelerations are prescribed as control inputs. The resulting necessary motor torques as well as system energy rates are computed for verification. Next, a novel control algorithm is developed from the stability constraint for reference trajectory tracking. In contrast to the control development for single-gimbal variable-speed gyros, a Newton-Raphson scheme is required to solve for the desired DGV control variables because they appear in cross product and quadratic form, preventing analytical solutions. Analysis of the control theory suggests that the same torque amplification effects exist as in a single-gimbal control moment gyro, but control by a single DGV device is not robust due to potential configurations that result in control singularities. When these singularities are avoided, a simulation with successful reference trajectory tracking is achieved. Allowing double-gimbal gyros to have variable wheel speeds provides additional torquing capabilities which is significant if failure modes are considered. As shown, a single DGV device can provide limited three-dimensional attitude control. [View Full Paper]

AAS 11 – 568

Single-Axis Pointing of a Magnetically Actuated Spacecraft: A Non-Nominal Euler Axis Approach

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The use of magnetic torquers on satellites flying inclined Low Earth Orbits (LEO) arises challenging problems when dealing with control strategies: since the available torque is perpendicular to the local magnetic field, the Attitude Control System (ACS) is inherently underactuated if no other attitude effector is available.

In this paper a rigorous proof of global asymptotic stability is derived for a control law that leads the satellite to a desired pure spin condition around a principal axis of inertia. A heuristic contribution is then added, inspired by quaternion feedback control and a previous geometric result obtained by the authors, which allows for pointing the spin axis along the normal to the orbital plane. [View Full Paper]

AAS 11 – 569

Solution of Spacecraft Attitude via Angular Momentum in Body and Inertial Frames

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Attitude solutions for spin-stabilized rigid spacecraft are presented that are direct functions of the torque and angular momentum vectors in the body and in the inertial frame. Two solutions are found: an approximate solution and an exact algebraic solution. Unfortunately, in applications, the algebraic method is not practical because the torque and angular momentum vectors usually are not precisely known in the inertial frame. The approximate method, which tolerates approximate values for the angular momentum vector in inertial space, is verified numerically for a spin-stabilized rigid spacecraft in the following three maneuver cases: 1) the spinning, thrusting problem, 2) the thrust ramp-up problem, and 3) the spin-up problem. The numerical results for the approximate method are accurate for small excursions of the inertial angular momentum vector from its initial orientation in space. However, for the same conditions the numerical investigations show that the results of the exact method are poor due to the error in the axial component of the torque in the inertial frame. [View Full Paper]

AAS 11 – 570

(Paper Withdrawn)

AAS 11 – 571

Attitude Control of the Spacecraft with Swiveling Orbit-Control Engine during the Propulsion

WenShu Wei, **Wuxing Jing** and **Yingjing Qian**, Department of Astronautics Engineering, Harbin Institute of Technology, Harbin, China

A research is presented to solve the problem that the thrust vector of swiveling engine on variable-mass vehicle could not only track changes of centroid position but also point to a fixed direction in inertial space. In this paper, the variable-mass vehicle is considered to be consisting of two parts—a two-way swiveling engine and a variable-mass platform. The mathematical model of the complex variable-mass system is established by using the Reynolds Migration Theorem. Besides, during the control system design, quaternion is converted into three quasi-Euler angles by means of a linear transformation and the on-off control law is designed on the phase plane which is formed by quasi-Euler angle and quasi-Euler angular velocity. The simulation results demonstrate the performance of the control law used on the variable-mass vehicle and therefore validate the viability of the control law. [View Full Paper]

AAS 11 – 572

Magnetometer-Only Attitude Determination Using Two-Step Extended Kalman Filter

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Determining spacecraft attitude in real time using only magnetometer data presents a challenging filtering problem. A flexible and computationally efficient method for solving the spacecraft attitude using only an inexpensive and reliable magnetometer would be a useful option for satellite missions, particularly those with modest budgets. The primary challenge is that magnetometers only instantaneously resolve two axes of the spacecraft attitude. Typically, magnetometers are used in conjunction with other sensors to resolve all three axes. However, by using a filter over an adequately long orbit arc, the magnetometer data can yield full attitude, and in real time. The method presented solves the problem using a two-step extended Kalman filter. In the first step, the magnetic field data are filtered to obtain the magnetic field derivative vector, which is combined with the magnetic field vector in the second step to fully resolve the attitude. A baseline scenario is developed, and a parametric study is conducted using the parameters of interest. [View Full Paper]

AAS 11 – 573
(Paper Withdrawn)

AAS 11 – 603

An Approach to Star Tracker Only Attitude and Rate Estimation Using Motion Blur

Tom Dzamba, **Christy Fernando** and **John Enright**, Department of Aerospace Engineering, Ryerson University, Toronto, Ontario, Canada

Attitude determination is one of the most fundamental processes that occur during a mission. Many different types of attitude sensors exist to satisfy a broad range of mission-specific pointing requirements. Star trackers lie on the upper end of this spectrum. Although they provide attitude accuracy on the order of arcseconds, they have drawbacks when its comes to availability. Various attitude estimators can be used to propagate attitude during starless periods but without any measurements these estimates degrade quickly. This paper describes an approach to acquire angular rate information directly from the shape of imaged stars. The aim of this study is to improve the performance of a star tracker only attitude determination system. [View Full Paper]

SESSION 19: ORBIT ESTIMATION II
Chair: Dr. Thomas Eller, Astro USA, LLC

AAS 11 – 574

Applications of the Admissible Region to Space-Based Observations

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Situational awareness of Earth-orbiting particles such as active satellites and space debris is highly important for all current and future space-faring nations. Previous research has proposed a correlation and initial orbit determination technique for ground based optical observations where multiple admissible region maps are intersected in the Poincare orbit element space. In this paper, a new application of the admissible region to space-based observations is introduced. A modification must be made to the correlation process as the observer's state is always a valid solution. Numerical examples for several observation scenarios are discussed, including LEO-on-GEO and GEO-on-GEO observations. [View Full Paper]

AAS 11 – 575

Coupling of Nonlinear Estimation and Dynamic Sensor Tasking Applied to Space Situational Awareness

Patrick S. Williams and **David B. Spencer**, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.;
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The following work examines a multi-object, multi-sensor nonlinear tracking problem, applied specifically to Space Situational Awareness (SSA). The SSA problem is concerned with the tracking, detection, and cataloging of space objects from both ground and space-based sensors and is characterized by having a large number of satellites to track versus few available sensors to track them. This discrepancy gives rise to situations where sensors have multiple satellites within their view and must decide which to observe and which to ignore within the limited time frame those observations remain available, a process known as 'sensor tasking' or 'sensor network management.' In order to make these tasking decisions, it is necessary to create some form of utility metric to determine which satellites are the most advantageous to observe out of all the possibilities available to all sensors at a particular instant of time. This paper will study the use of utility metrics from the expected information gain for each object-sensor pair as well as the approximated stability of the estimation errors in order to work towards an optimal tasking strategy. Furthermore, the paper will investigate the coupling of these tasking strategies to two nonlinear estimators which will provide state and uncertainty estimates throughout the tracking simulations. The investigation of this coupling will demonstrate that the use of more accurate estimators leads to better overall estimates, not only due to the advantages within the estimation methods, but also from the improvement in tasking decisions due to selection of these estimators.
[View Full Paper]

AAS 11 – 576

Covariance-Driven Sensor Network Tasking for Diverse Space Objects

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Previous studies have shown that using covariance information for scheduling observations of resident space objects (RSOs) can lead to significant improvements in orbit determination accuracy. That was done by maximizing the effectiveness of observations in reducing some measure of uncertainty in the RSO orbit state, but results were shown for a limited set of RSOs which were all in similar orbits. In this study, methods are presented that use covariance to drive the sensor scheduling for observations and which are applicable to RSOs in diverse orbit regimes and where some RSOs are given a higher priority than others. [View Full Paper]

AAS 11 – 577
(Paper Withdrawn)

AAS 11 – 578

Maneuver Event Detection and Reconstruction Using Body-Centric Acceleration/Jerk Optimization

Daniel L. Oltrogge, AGI's Center for Space Standards and Innovation, Colorado Springs, Colorado, U.S.A.

Maneuver detection and calibration for arbitrary satellites observed using Non-Cooperative Tracking techniques is a challenging problem. In this paper, we derive new burn reconstruction models capable of performing long-duration maneuvers better suited to Earth-pointing satellites whose body frame axes are either velocity-, radial, or inertially-aligned. We then attempt to reconstruct unknown maneuvers using only the pre- and post-burn ephemerides and the new velocity-aligned reconstruction technique. Maneuver start and stop time are determined by minimizing the weighted position and velocity residuals at the end of the burn. We then compare the optimized burn conditions with simulated actual burn conditions. [View Full Paper]

AAS 11 – 579

Satellite Location Uncertainty Prediction

Felix R. Hoots, Systems Analysis and Simulation Subdivision, The Aerospace Corporation, Chantilly, Virginia, U.S.A.

The location of a satellite in space is typically described by an element set or state vector at some epoch time and the location uncertainty is described by a covariance. The probability density function is usually assumed to be Gaussian. Nonlinearities can introduce significant errors in the propagation of the covariance and have been a topic of several recent papers. We have developed a method to remove most of the nonlinearities and provide accurate propagation of the uncertainty estimate for 30 days or more. The accuracy of the predicted uncertainty estimate is within a few percent when compared to Monte Carlo simulation. [View Full Paper]

AAS 11 – 580

Simulating Space Surveillance Networks

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Generating observations for satellites is a difficult process because actual observations are usually withheld and sensor locations and performance are often unknown. While many tools exist, a comprehensive listing of sensor locations and characteristics is difficult to find. When sensor locations are known, the specific tracking frequency is very difficult to model as the observations generally result from ad hoc tasking directives, implemented by each sensor with individual constraints. Sensor operational open and close dates are not well known either for historical purposes. This paper summarizes open source data to establish a baseline of sensor locations, primarily using Google Earth. We also discuss techniques to accurately simulate the observations and arrive at realistic scheduling densities. [View Full Paper]

AAS 11 – 581

Solar Radiation Pressure Binning for the Geosynchronous Orbit

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Orbital maintenance parameters for individual satellites or groups of satellites have traditionally been set by examining orbital parameters alone, such as through apogee and perigee height binning; this approach ignored the other factors that governed an individual satellite's susceptibility to non-conservative forces. In the atmospheric drag regime, this problem has been addressed by the introduction of the "energy dissipation rate," a quantity that represents the amount of energy being removed from the orbit; such an approach is able to consider both atmospheric density and satellite frontal area characteristics and thus serve as a mechanism for binning satellites of similar behavior. The geosynchronous orbit (of broader definition than the geostationary orbit—here taken to be from 1300 to 1800 minutes in orbital period) is not affected by drag; rather, its principal non-conservative force is that of solar radiation pressure—the momentum imparted to the satellite by solar radiometric energy. While this perturbation is solved for as part of the orbit determination update, no binning or division scheme, analogous to the drag regime, has been developed for the geosynchronous orbit. The present analysis has begun such an effort by examining the behavior of geosynchronous rocket bodies and non-stabilized payloads as a function of solar radiation pressure susceptibility. A preliminary examination of binning techniques used in the drag regime gives initial guidance regarding the criteria for useful bin divisions. Applying these criteria to the object type, solar radiation pressure, and resultant state vector accuracy for the analyzed dataset, a single division of "large" satellites into two bins for the purposes of setting related sensor tasking and OD controls is suggested. When an accompanying analysis of high area-to-mass objects is complete, a full set of binning recommendations for the geosynchronous orbit will be available. [View Full Paper]

AAS 11 – 582

Space Object Tracking in the Presence of Attitude-Dependent Solar Radiation Pressure Effects

Kyle J. DeMars, National Research Council (NRC), Air Force Research Laboratory, Kirtland AFB, New Mexico; **Robert H. Bishop**, College of Engineering, Marquette University, Milwaukee, Wisconsin, U.S.A.; **Moriba K. Jah**, Air Force Research Laboratory Space Vehicles Directorate, Kirtland AFB, New Mexico, U.S.A.

The tracking of space objects (SOs) is often accomplished via measurement systems such as optical telescopes, where the observations occur infrequently, leading to long periods of time in which the SO uncertainty must be propagated. Given that the uncertainty associated with an SO is described by a probability density function (pdf), the infrequent measurements and subsequent long arcs of propagation lead to difficulties in reacquisition due to inaccurate methods for the propagation of the pdf. The standard methods for propagation of the pdf are typically those of the extended Kalman filter (EKF) or unscented Kalman filter (UKF) which make use of only the first two moments of the pdf, thereby limiting their ability to accurately describe the actual pdf. This work examines an improved propagation scheme which allows for the pdf to be represented by a Gaussian mixture model (GMM) that is adapted online via splitting of the GMM components based on the detection of nonlinearity during the propagation. In doing so, the GMM approximation adaptively includes additional components as nonlinearity is encountered and can therefore be used to more accurately approximate the pdf. The improved representation of the uncertainty region of the SO can then be used to more consistently reacquire SOs, thereby improving the overall tracking of space objects. It is shown (via simulation) that the improved propagation scheme leads to a more realistic and accurate representation of the region of uncertainty. Furthermore, when the more accurately propagated uncertainty is fused with incoming measurement data, it is shown that the resultant updated uncertainty more accurately represents the true state and yields a smaller region of uncertainty. [View Full Paper]

SESSION 20: SPACECRAFT AUTONOMY

Chair: Dr. Craig McLaughlin, University of Kansas

AAS 11 – 583

Applications of Artificial Potential Function Methods to Autonomous Space Flight

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The goal of this investigation is to identify a systematic approach for the determination of accurate startup arcs for autonomous spacecraft path planning and guidance. This capability is of particular interest for on-demand onboard determination. Artificial potential function methods are common in the field of path planning. However, the resulting control requirements are not always feasible in practice due to various hardware and mission constraints. Still, the general concept is useful in the determination of suitable startup arcs for autonomous algorithms that are capable of addressing these actuator constraints on demand. [View Full Paper]

AAS 11 – 584

Autonomous Optimal Deorbit Guidance

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This work presents a study on autonomous guidance of deorbit maneuvers. The problem is for a vehicle to autonomously execute a minimum-fuel, finite-time deorbit maneuver that achieves desired entry interface conditions. The guidance problem is formulated as an optimal control problem with a multiple burn trajectory structure. Depending on the initial vehicle's orbit, more than one burn may yield the smallest fuel expenditure. This work explores the different finite-time burn maneuvers to yield the optimal deorbit guidance solution. More specifically, the differences between the single and multiple burn(s) are explored. General entry interface targeting conditions are formulated to allow variable dependence among flight path angle, velocity, and range-to-go. The linear relationship between the entry interface flight path angle and velocity used by the Space Shuttle is shown to be a special case of this general formulation. For numerical solutions, an analytical multiple-shooting algorithm is used. Numerical simulation results are provided to demonstrate the method. [View Full Paper]

AAS 11 – 585

Autonomous Precision Orbit Control for Earth-Referenced Flight Path Repeat

Toru Yamamoto, **Isao Kawano**, **Takanori Iwata**, **Yoshihisa Arikawa** and **Hiroyuki Itoh**, Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, Japan; **Masayuki Yamamoto** and **Ken Nakajima**, Mitsubishi Space Software Co., Ltd., Tsukuba, Ibaraki, Japan

Recently satellites with synthetic aperture radars (SAR) have stringent requirements to achieve precise orbit control of Earth-referenced repeating orbits for effective repeat-pass SAR interferometry. Frequent orbit maneuvers are necessary, which burdens daily ground operations. To achieve high accuracy with low workload, a new autonomous orbit control method has been studied. Both in-plane and out-of-plane maneuvers are performed autonomously and the "maneuver slot" concept is applied to allow the on-board algorithm to determine the maneuver timing and avoid conflicts with mission observation. There are plans to apply the outcome of this research in practical use for the Japanese Earth observation satellite ALOS-2. [View Full Paper]

AAS 11 – 586

Design and Flight Implementation of Operationally Relevant Time-Optimal Spacecraft Maneuvers

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This paper presents the flight implementation of an operationally relevant time-optimal maneuver experiment on the TRACE spacecraft. The objective is to demonstrate time-optimal maneuvering capabilities within the context of a typical operational scenario, such as scientific data collection, in which a spacecraft is required slew to various orientations in succession. The time-optimal maneuvers are designed by constructing an appropriate optimal control problem formulation based on a detailed model of the reaction wheel spacecraft dynamics. The high-dimensional optimization model includes practical constraints on the spacecraft performance including the nonlinear reaction wheel torque-momentum envelope and is solved using the Legendre pseudospectral method. The flight results demonstrate that time-optimal maneuvers can be designed and predictably executed within the specified limits. Moreover, the results of the flight experiment show clearly that the application of Legendre pseudospectral method for time-optimal maneuver design can extend the capabilities of the spacecraft over a wide envelope without the need to reconfigure or otherwise modify the existing spacecraft attitude control system. [View Full Paper]

AAS 11 – 587

Designing Stable Iterative Learning Control Systems from Frequency Based Repetitive Control Designs

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Repetitive control (RC) and iterative learning control (ILC) design control systems that aim for zero tracking error in repeating situations. ILC applies to spacecraft problems that perform repeated scanning maneuvers with a fine pointing instrument. Very effective RC design methods use steady state frequency response approaches. They cannot be applied directly to ILC because ILC is a finite time problem, and asks for zero error not only in the part of the desired trajectory after transients have decayed, but also asks for zero error during the transients as well. This work converts these effective RC design methods so that they apply to the ILC problem, and produce convergence to zero tracking error that is monotonic with iterations in the sense of the Euclidean norm. One first fills the ILC gain matrix with the RC gains, and then adjusts a few gains associated with the first few time steps, using a steepest descent or other similar algorithm. We show that adjusting only one gain can be sufficient to produce asymptotic stability and monotonic convergence. The method is simple to apply, and allows one to make use of a very effective RC design method in ILC applications, and represents a powerful way to apply frequency response ideas to finite time ILC problems. [View Full Paper]

AAS 11 – 588

Optimal Feedback Guidance Algorithms for Planetary Landing and Asteroid Intercept

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Optimal feedback guidance algorithms are investigated for planetary landing or asteroid intercept/rendezvous missions with a variety of terminal velocity constraints. This paper examines the well-known problems of constrained-terminal-velocity guidance (CTVG), free-terminal-velocity guidance (FTVG), and intercept-angle-control guidance (IACG), and presents some new results. It is shown that FTVG has a local optimal solution of the time-to-go for a certain set of initial conditions. It is also shown that a simple combination of the CTVG and FTVG algorithms can be employed for an intercept-angle control problem. Some inherent relationships of these optimal feedback guidance algorithms with the classical proportional navigation guidance (PNG), augmented PNG, biased PNG, and the zero-effort-miss (ZEM) and zero-effort-velocity (ZEV) feedback guidance are also discussed. [View Full Paper]

AAS 11 – 589

On Multi-Input Multi-Output Repetitive Control Design Methods

Richard W. Longman, Department of Mechanical Engineering, Columbia University New York, New York, U.S.A.; **Jer-Nan Juang**, Department of Engineering Science, National Cheng Kung University, Tainan, Taiwan; **Minh Q. Phan**, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, U.S.A.; **Kevin Xu**, Department of Electrical Engineering, Columbia University, New York, New York, U.S.A.

Repetitive control (RC) can address the common spacecraft jitter problem for fine pointing equipment resulting from small imbalance in reaction wheels or CMG's. This problem requires multi-input, multi-output (MIMO) RC design methods. A previous papers by the authors developed a rather comprehensive stability theory for MIMO repetitive control, and suggests design methods whose performance is studied here. One approach stays on the MIMO level and minimizes a Frobenius norm summed over frequencies from zero to Nyquist. And it produces a matrix compensator composed of FIR filters. The second approach reduces the problem to a set of SISO design problems, one for each input-output pair. The latter approach allows one to make use of experience gained in SISO designs. Both approaches are seen here to be able to create RC designs with fast monotonic decay of the tracking error. Choice of the FIR filter order and the choice of the number of non-causal gains, although critical in some SISO low order designs, does not appear to be an important issue in MIMO designs using reasonably large order. [View Full Paper]

AAS 11 – 590

Satellite Position and Attitude Control by On-Off Thrusters Considering Mass Change

Yasuhiro Yoshimura, **Takashi Matsuno** and **Shinji Hokamoto**, Department of Aeronautics and Astronautics, Kyushu University, Nishi-ku, Fukuoka, Japan

This paper deals with the two-dimensional position and attitude control of a satellite by on-off thrusters which are fixed to the satellite's body. Since the thrusters generate constant and unilateral forces, the equations of motion form nonholonomic constraint and cannot be integrated. Furthermore, the satellite's mass changes due to the fuel consumption. Utilizing Fresnel integrals and the partial integrals, we derive the approximate analytic solution considering the satellite's mass change to achieve a specified satellite's position and attitude. The accuracy of the proposed approximate technique is verified by applying it to a condition considered in SLIM project of JAXA.
[View Full Paper]

AAS 11 – 591

Stabilizing Intersample Error in Iterative Learning Control Using Multiple Zero Order Holds Each Time Step

Te Li, **Richard W. Longman** and **Yunde Shi**, Department of Mechanical Engineering, Columbia University New York, New York, U.S.A.

Iterative learning control (ILC) aims for zero tracking error in a control system that performs the same tracking command repeatedly. Spacecraft applications include repeated scanning maneuvers with fine pointing equipment. Previous research shows that zero tracking error every step results in a finite time sample of an unstable control action, with the error between time steps growing exponentially with time step. This paper considers a generalized hold, allowing extra zero order hold values within each time step. These extra control actions are seen to eliminate this problem. In addition, it is shown how to use the extra freedom to minimize the tracking error at times between the addressed time steps. The control action is chosen to minimize a penalty function on both error and control effort based on a quadratic cost. This approach is studied mathematically and in simulations, and shown to make a promising method of addressing a fundamental theoretical problem in iterative learning control. [View Full Paper]

AAS 11 – 592

Tracking Control of Nanosatellites with Uncertain Time Varying Parameters

D. Thakur and **B. G. Marchand**, Department of Aerospace Engineering, The University of Texas at Austin, Texas, U.S.A.

The focus of this study is an adaptive control scheme that maintains consistent satellite attitude tracking performance in the presence of uncertain time-varying inertia parameters. Potentially large variations in the inertia matrix may occur due to changes in fuel mass, fuel slosh, and deployable appendages such as booms and solar arrays. As such, the assumption of a constant inertia matrix may not suffice for precise tracking maneuvers. The present investigation develops an appropriate description for a class of time-dependent inertia uncertainty. An adaptive control law is implemented to recover closed-loop stability and accurate attitude and angular velocity tracking in the face of such parametric uncertainty. [View Full Paper]

SESSION 21: ORBITAL DEBRIS II
Chair: Dr. Felix Hoots, The Aerospace Corporation

AAS 11 – 593

Attitude Control and Orbital Dynamics Challenges of Removing the First 3-Axis Stabilized Tracking and Data Relay Satellite from the Geosynchronous Arc

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Dave Olney and **Ronald Zaleski**, NASA-GSFC, Greenbelt, Maryland, U.S.A.

Launched on April 4, 1983 onboard STS–6 (Space Shuttle *Challenger*), the First Tracking and Data Relay Satellite (TDRS–1) was retired above the Geosynchronous Orbit (GEO) on June 27, 2010 after having provided real-time communications with a variety of low-orbiting spacecraft over a 26-year period. To meet NASA requirements limiting orbital debris, a team of experts was assembled to conduct an End-Of-Mission (EOM) procedure to raise the satellite 350 km above the GEO orbit. Following the orbit raising via conventional station change maneuvers, the team was confronted with having to deplete the remaining propellant and .passivate. all energy storage or generation sources. To accomplish these tasks within the time window, communications (telemetry and control links), electrical power, propulsion, and thermal constraints, a spacecraft originally designed as a three-axis stabilized satellite was turned into a spinner. This paper (a companion paper to “Innovative Approach Enabled the Retirement of TDRS–1,” paper # 1699, IEEE 2011 Aerospace Conference, March 5–12, 2011) focuses on the challenges of maintaining an acceptable spinning dynamics, while repetitively firing thrusters. Also addressed are the effects of thruster firings on the orbit characteristics and how they were mitigated by a careful scheduling of the fuel depletion operations. Periodic thruster firings for spin rate adjustment, nutation damping, and precession of the momentum vector were also required in order to maintain effective communications with the satellite. All operations were thoroughly rehearsed and supported by simulations thus lending a high level of confidence in meeting the NASA EOM goals.
[View Full Paper]

AAS 11 – 594

Averaged Dynamics of HAMR Objects: Effects of Attitude and Earth Oblateness

Aaron Rosengren and **Daniel Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Colorado, U.S.A.

High area-to-mass ratio (HAMR) objects in high-Earth orbit are subject to strong solar radiation pressure (SRP) effects in addition to higher-order Earth gravity field and luni-solar perturbations. The dynamics of these objects have been explored in recent years, finding extreme variations in eccentricity and inclination due to these combined effects. This paper describes the effects of debris attitude on the averaged solution to the SRP perturbed orbiter problem. For an arbitrary model of SRP, we show that the secular problem yields an explicit closed-form solution. The details of the solution rely only on the inverse square character of the SRP force, and not on the specific body characteristics. We also find that if the net direction in which the SRP acceleration acts lies within the Earth heliocentric orbit plane, the object has similar dynamics to a cannonball. If the orientation changes with respect to the Sun-line, the object can evolve through a variety of solutions characterized by the SRP perturbation angle. Finally, we show how our current SRP-only averaged results can be modified to include perturbations from the Earth's oblateness (J2). The averaged orbital motion of HAMR cannonball objects in the presence of SRP and J2 is simulated for test objects released in GEO. Inclusion of the secular effects of J2 brings our model in closer agreement with the numerical computations of earlier researchers. [View Full Paper]

AAS 11 – 595

Effective Strategy to Identify Origins of Fragments from Breakups in GEO

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This paper proposes a search strategy to effectively detect and identify fragments from breakups in the geosynchronous earth orbit (GEO) based on orbital debris modeling techniques. The modeling techniques describe debris generation and propagation to predict population and motion of fragmentation debris from breakups. This search strategy is superior to the existing survey observations in terms of the efficiency on origin identification of fragments from breakups. This paper demonstrates how the search strategy distinguishes features of two breakups and identifies the origins of detected fragments as a corresponding breakup. [View Full Paper]

AAS 11 – 596
(Paper Withdrawn)

AAS 11 – 597

Uncertainty in Lifetime of Highly Eccentric Transfer Orbits Due to Solar Resonances

Alan B. Jenkin and **John P. McVey**, Astrodynamics Department, The Aerospace Corporation, El Segundo, California, U.S.A.;
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Disposal orbit studies performed by the authors over many years have shown that highly eccentric transfer orbits can have significant variability in orbital lifetime. The resulting uncertainty in predicted lifetime has made it difficult to assess compliance with disposal requirements. In this study, the cause of the lifetime variability was investigated by multi-processor precision long-term integration and inspection of the orbital element equations of variation. Results showed that lifetime variability is caused by solar resonances. The effect of these resonances cannot be predicted for commonly used transfer orbits, making it difficult to assure disposal compliance. [View Full Paper]

SESSION 22: ATTITUDE D&C II
Chair: Renato Zanetti, The Charles Stark Draper Laboratory

AAS 11 – 598

An Extended Kalman Smoother for the DICE Mission Attitude Determination Post Processing with Double Electrical Field Probe Inclusion

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R. Fullmer, Department of Mechanical and Aerospace Engineering, Utah State University, Logan, Utah, U.S.A.

This paper describes implementation and verification of a post-processing attitude determination tool for the DICE spacecraft. The DICE mission represents a constellation of two spin-stabilized CubeSats used for probing the native electrical field of the Earth. The DICE mission is scheduled for launch in September 2011. Each DICE spacecraft is equipped with a GPS receiver, a Sun Sensor and a Magnetometer. The data from the Double Electrical Field Probe is to be included in the attitude solution. The attitude post-processing determination tool is based on two optimal quaternion-based Kalman filters. Those filters are combined together in one fixed-interval Extended Kalman Smoother. Simulated results showed that the Extended Kalman Smoother can effectively reduce the covariance of the estimation by 40%. This paper also extents previous research into incorporating data from the Double Electrical Field Probe science sensors into the attitude solution. It shows that using Double Electrical Field Probes combined with a Magnetometer can improve the attitude accuracy about 3 times in the eclipse. Hence, the combination of a Magnetometer and Double Electrical Field Probes improves attitude solution for low cost missions when in eclipse, when the sun is not in the Field of View or when the spacecraft is spin stabilized and, consequently, cannot use a star tracker. The simulated results also show that the improvement in the estimation is not constant but it depends on the spacecraft position on the orbit.
[View Full Paper]

AAS 11 – 599

Experimental Testing of the Accuracy of Attitude Determination Solutions for a Spin-Stabilized Spacecraft

Keegan Ryan and **Rees Fullmer**, Department of Mechanical and Aerospace Engineering, Utah State University, Logan, Utah, U.S.A.;
Steve Wassom, Space Dynamics Laboratory, Logan, Utah, U.S.A.

Spin-stabilized spacecraft rely on sun and three-axis magnetic field sensor measurements for attitude determination. This study experimentally determines the accuracy of attitude determination solutions using modest quality sensors. A test cell with a spacecraft simulator is used to collect solar and magnetic data during spinning motion. Attitude estimates using various algorithms are generated and compared to the experimentally measured attitude. The propagation of these solutions without the sun are presented. Once the accuracy of the test cell is known, it will be used to evaluate the attitude determination system of the DICE spacecraft prior to flight. [View Full Paper]

AAS 11 – 600

Initial Attitude Analysis of the RAX Satellite

John C. Springmann and **James W. Cutler**, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.

This paper discusses sun sensor calibration and initial results of on-orbit attitude estimation for the Radio Aurora Explorer (RAX) satellite. RAX is a triple CubeSat that was launched November 19, 2010. RAX utilizes a passive magnetic attitude control system and magnetometers, coarse sun sensors, and a three-axis rate gyroscope for attitude determination. Sample data from the attitude sensors is shown to motivate on-orbit sensor calibration. A batch least-squares algorithm was developed to estimate the maximum current output of the sun sensors (photodiodes), which is a critical parameter for the measured sun vector. The calibration algorithm is one of two focuses of this paper. The second focus is the extended Kalman filter used for attitude estimation. The implementation, tuning, and results of filtering are presented. When RAX is in the sun, the 99% bound on total angular attitude accuracy varies between 3º and 8º; the 68% error bound is between 1.7º and 4º. [View Full Paper]

AAS 11 – 601
(Paper Withdrawn)

AAS 11 – 602

A Spectral Star Tracker Using a CFA Detector

Geoffrey R. McVittie and **John Enright**, Department of Aerospace Engineering, Ryerson University, Toronto, Ontario, Canada

In this study, we investigate the measurement and estimation of star colour properties for a new spectral star tracker. A colour-filter-array (CFA) detector modifies a conventional star tracker to sample different regions of a stars spectral emission profile. We adapt conventional monochromatic centroid estimation techniques, such as arithmetic first moment approximation and curve-fitting, to extract colour information from the observed star spot images. Particular attention focuses on the precision of the colour estimates and effects the CFA sampling induces on the colour and centroid estimates. A combination laboratory testing and empirical observations, made using a prototype optics/detector hardware configuration, validates the techniques. [View Full Paper]

AAS 11 – 603

(See Session 18)

SESSION 23: ORBIT ESTIMATION III
Chair: Bob Glover, AT&T

AAS 11 – 604

Application of the Transformation of Variables Technique for Uncertainty Mapping in Nonlinear Filtering

Ryan M. Weisman, **Manoranjan Majji** and **Kyle T. Alfriend**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

This work addresses the impact nonlinear observations of state variables have on uncertainty accuracy associated with state estimation algorithms. The transformation of variables technique is applied to exactly map probability density functions between domains completely spanned by different combinations of basis vectors. The technique allows for proper generation of the likelihood density when converting from measurement to state variable space and for association of a present state distribution with prior observation data. The exact mapping of probability density functions between domains and proper characterization of prior knowledge allows for Bayesian estimation to be appropriately carried out. [View Full Paper]

AAS 11 – 605

Computational Efficiency of a Hybrid Mass Concentration and Spherical Harmonic Modeling

Nathan Piepgrass and **David Geller**, Mechanical and Aerospace Engineering Department, Utah State University, Logan, Utah, U.S.A.

Through spherical harmonics, one can describe complex gravitational fields. However, as the order and degree of the spherical harmonics increases, the computation speed rises exponentially. In addition, for onboard applications of spherical harmonics, the processors are radiation hardened in order to mitigate negative effects of the space environment on electronics. But, those processors have outdated processing speeds, resulting in a slower onboard spherical harmonic program. This paper examines a partial solution to the slow computation speed of spherical harmonics programs. The partial solution was to supplant the gravity models in the flight software. The spherical harmonics gravity model can be replaced by a hybrid model, a mass concentrations model and a secondary (lesser degree or order) spherical harmonics model. To compute the mass values for the mass concentration model, a potential estimation scheme was selected. In that scheme, mass values were computed by minimizing the integral of the difference between the correct and the estimated potential. The best hybrid model for the 8 degree and 8 order, 15 degree and 15 order, and 30 degree and 30 order lunar potential fields is developed following three different approaches: potential zeros method, gravitational anomalies method, and iterative method. Afterwards, the accuracy and improvement in processing speed between the hybrid model and a lunar spherical harmonic model are evaluated. [View Full Paper]

AAS 11 – 606

Evaluation of the Information Content of Observations with Application to Sensor Management for Orbit Determination

Kyle J. DeMars and **Moriba K. Jah**, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

Information regarding the state of a space object (SO) is typically inferred via measurement systems such as optical telescopes or radar systems. As the measurement systems become more advanced, a greater number of SOs can be detected which leads to an ever-increasing number of SOs that need to be uniquely identified. Given the lack of ubiquitous observations, scarce sensor resources must be optimally utilized, i.e. so that the telescope or radar systems are not tasked to acquire redundant or useless information. Additionally, in the situation where multiple systems can observe the same object, the observation geometry needs to be accounted for so that the sensor which can provide the most information is employed, enabling other sensors to dedicate their time to observing other objects. This leads to a need for methods which evaluate the information gain (ambiguity reduction) that can be expected from any given sensor observing any given SO. To address this need, this work examines several information-theoretic approaches to determining the information content of observations and compares the different developed methods in the context of assessing the measurement utility and observation scheduling for orbit determination problems. [View Full Paper]

AAS 11 – 607

QQ-Plot for Sequential Orbit Determination

James R Wright, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

Use of the Kalman measurement update theorem for sequential orbit determination incurs *the requirement*, from fundamental hypothesis, that post-fit measurement residual ratios have a standard normal distribution. When the residual sample size is small, comparison to the normal density curve is not useful because small-sample normal ensembles do not resemble the infinite-ensemble normal curve (bell curve). The quantile-quantile (QQ) plot with Royston-Michael acceptance boundaries for normal distributions is useful for small and large ensembles. Herein I demonstrate the application of QQ-Plots to simulated measurement residual ratios. On real data, QQ-Plots will be used to demonstrate, or deny, that *the requirement* is satisfied. [View Full Paper]

AAS 11 – 608

Sparse Grid-Based Orbit Uncertainty Propagation

Matthew D. Nevels, **Bin Jia**, **Matthew R. Turnowicz**, **Ming Xin** and **Yang Cheng**, Department of Aerospace Engineering, Mississippi State University, Mississippi State, Mississippi, U.S.A.

A sparse grid-based orbit uncertainty propagation method is presented. The idea of the method is to represent the initial orbit uncertainty by a six-dimensional sparse grid, propagate each and every sparse grid point individually through the nonlinear orbit dynamics, and compute the statistical moments, e.g., mean and covariance, of the orbit from the propagated sparse grid points. The Smolyak rule is used to generate the sparse grid through linear combinations of low-level tensor products. The sparse grid method is a generalization of the Unscented Transformation (UT) of the Unscented Kalman Filter and can achieve higher accuracy than UT. It is more efficient than the dense grid method and more efficient and more accurate than the Monte Carlo method and the Quasi-Monte Carlo method in moment computation. [View Full Paper]

SESSION 24: SPACE ENVIRONMENT
Chair: Dr. Matthew Berry, Analytical Graphics, Inc.

AAS 11 – 475
Combining Precision Orbit Derived Density Estimates

Dhaval Mysore Krishna and **Craig A. McLaughlin**, Department of Aerospace Engineering, University of Kansas, Lawrence, Kansas, U.S.A.

This research creates continuous data sets and improves the atmospheric density estimates obtained from the precision orbit ephemerides (POE) for the Challenging Minisatellite Payload (CHAMP), and Gravity Recovery And Climate Experiment (GRACE) satellite during the 2 hour overlap periods at the beginning and end of the 14 hour solution fit span. Two approaches are followed; the first method is to blend the density data during the two hour overlap period using the linear weighted blending technique and the second method is to blend the POE position vectors using the same linear weighted blending technique, and use them as measurements in the orbit determination to estimate the densities. The accuracy of the density estimates was evaluated quantitatively by calculating their cross correlation with respect to the accelerometer derived density from the accelerometers onboard CHAMP and GRACE. The results showed that the linear weighted blending of POE derived density had the highest correlation with accelerometer derived density for both CHAMP and GRACE.
[View Full Paper]

AAS 11 – 609
Density and Ballistic Coefficient Estimation Revisited

Piyush M. Mehta and **Craig A. McLaughlin**, Department of Aerospace Engineering, University of Kansas, Lawrence, Kansas, U.S.A.

Orbit determination and prediction for low Earth orbit satellites depend highly on atmospheric density modeling. This paper examines the effects of ballistic coefficient errors in using precision orbit ephemerides (POE) as measurements to estimate total density along the satellite orbit. A precision orbit determination process is used to estimate density using Challenging Minisatellite Payload and Gravity Recovery and Climate Experiment precision orbit data. The paper also examines the simultaneous estimating of density and ballistic coefficient. POE derived densities correlate well with accelerometer derived densities, but density error does have some inverse correlation with estimated ballistic coefficient. [View Full Paper]

AAS 11 – 610

Global Atmospheric Density Estimation Using a Sequential Filter/Smoother

James W. Woodburn and **John H. Seago**, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

Sequential estimation algorithms are applied to the problem of global atmospheric density estimation. An optimal sequential filter is combined with a variable lag smoother to investigate the estimation of corrections to intermediary temperature parameters in the Jacchia 1970 atmospheric density model. Of specific interest are the time lag required to provide the most accurate definitive estimates of temperature corrections, and the observability and correlation associated with several parameterizations of the temperature corrections. [View Full Paper]

AAS 11 – 611

Mini-Satellite for Drag Estimation (MinDE): A Satellite as a Sensor System

Kyle Fanelli and **Bogdan Udrea**, Embry Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.; **Federico Herrero**, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Determining an accurate model of the atmosphere between 200-500km requires accurate measurements of total densities and composition. To do this, drag coefficients must be predicted with a level of accuracy surpassing previous drag satellites. This is achieved using the momentum transfer ratio and expressing the drag coefficient in terms of measurable momentum transfer parameters, and simulated using rarefied gas dynamics. The goal is to use a satellite with a complex shape which has a very well defined drag coefficient, along with highly accurate accelerometers and miniaturized mass spectrometers, to reduce the uncertainty of the drag measurement to 1% or less. This paper is a study into the physical results of such a theoretical model and the challenges with its design. [View Full Paper]

AAS 11 – 612 **(See Session 17)**

AAS 11 – 613

Time Periods of Anomalous Density for GRACE and CHAMP

Craig A. McLaughlin, **Eric Fattig**, **Dhaval Mysore Krishna**, **Travis Locke** and **Piyush M. Mehta**, Department of Aerospace Engineering, University of Kansas, Lawrence, Kansas, U.S.A.

While developing precision orbit ephemeris (POE) derived densities for GRACE and CHAMP, several periods have been found when the correlation between the POE derived density and accelerometer derived density is very low. The primary time period where this occurs is from October 2005 to January 2006 for GRACE. This time period includes the maneuvers required for the GRACE satellites to switch positions, but extend well before and after this event. The low correlations also exist between HASDM and accelerometer derived densities for this time period. This paper characterizes these time periods and attempts to explain the anomalous behavior. [View Full Paper]

SESSION 25: TRAJECTORY OPTIMIZATION III
Chair: Dr. Roby Wilson, Jet Propulsion Laboratory

AAS 11 – 614
A Linear Correction Approach for Precision Interplanetary Transfer Trajectory Design

Zhong-Sheng Wang and **Paul V. Anderson**, Embry Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.

The iteration process may not converge when linear correction is applied in precision interplanetary transfer trajectory design. To solve this problem, this paper proposes an improved two-step procedure for precision transfer trajectory design. First, the approximate values of perigee parameters are found using a two-body analysis (lunar missions) or patched conic analysis (Mars missions). Second, the “rope-climbing” algorithm is applied to determine the accurate values of the perigee parameters. The basic idea of the algorithm is to apply a series of linear corrections to solve the targeting problem of a nonlinear dynamic system. Numeric examples show that this procedure works effectively. [View Full Paper]

AAS 11 – 615
A Survey of Mission Opportunities to Trans-Neptunian Objects

Ryan McGranaghan, **Brent Sagan**, **Gemma Dove**, **Aaron Tullos**, **J. E. Lyne** and **Joshua P. Emery**, The University of Tennessee, Knoxville, Tennessee, U.S.A.

Preliminary designs for high thrust, flyby missions to five large trans-Neptunian Objects are discussed, with an emphasis on Quaoar, but also including Sedna, Makemake, Haumea, and Eris. The primary focus of this study was the design of the interplanetary trajectory for Earth departure dates between 2014 and 2050. The best trajectories identified use only a Jupiter gravity assist, require a total mission delta-V as low as 7.15 km/s and have arrival V_∞ values at the target comparable to those of the New Horizons mission to Pluto. Transit times range from 13.57 years for missions to Quaoar to 24.48 years to reach Sedna and Eris. Jupiter periapse radius is a critical factor for these missions, with satisfactory trajectories requiring values ranging from 3.5 to 25 planetary radii. [View Full Paper]

AAS 11 – 616

Application of Multiobjective Design Exploration to Solar-C Orbit Design

Akira Oyama, Department of Space Transportation Engineering, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Yasuhiro Kawakatsu**, Department of Space Systems and Astronautics, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Kazuko Hagiwara**, Space Systems Department, Mitsubishi Space Software Co. Ltd., Tsukuba, Japan

Multiobjective design exploration (MODE) framework is applied to the trajectory design optimization problem for SOLAR-C Plan A solar electric propulsion option. Present approach presents many designs that are better than the nominal design in all design objectives. Present approach also revealed some important design knowledge such as tradeoff information among maximization of final mass, maximization of final velocity, and maximization of minimum distance from the Sun. Present study also shows possibility of simultaneous design of trajectory and spacecraft. [View Full Paper]

AAS 11 – 617
(Paper Withdrawn)

AAS 11 – 618
(Paper Withdrawn)

AAS 11 – 619
(Paper Withdrawn)

AAS 11 – 620

Multi-Gravity-Assist Trajectories Optimization: Comparison between the Hidden Genes and the Dynamic-Size Multiple Populations Genetic Algorithms

Ossama Abdelkhalik, Department of Mechanical Engineering-Engineering Mechanics, Michigan Tech University, Houghton, Michigan, U.S.A.

The problem of optimal design of a multi-gravity-assist space trajectory, with free number of deep space maneuvers (MGADSM), poses a multi-modal cost function. In the general form of the problem, the number of design variables is solution dependent. This paper presents a comparison between two recently developed genetic-based methods to handle global optimization problems where the number of design variables vary from one solution to another. The first method is the hidden genes genetic algorithms (HGGA) and the second method is the dynamic-size multiple populations genetic algorithms (DSMPGA). In this paper, both methods are used to find solutions for the Jupiter Europa Orbiter mission. [View Full Paper]

AAS 11 – 621

Orbital Stability around Planetary Satellites as Optimization Problem

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E. Mooij and **R. Noomen**, Delft University of Technology, Delft, The Netherlands

This paper explores the problem of orbital stability of spacecraft around planetary satellites (*i.e.*, moons) under the influence of the gravitational pull of the primary planet. An overview is given of the currently available methods to define long-term stable orbits. Two new methods that are presented here aim to treat the problem of long-term orbital stability around planetary satellites as an optimization problem, in order to achieve flexibility in space mission design and to overcome the problems involved in averaging theories. The new methods differ in terms of definition of the objective function, thus providing differences in performance and applications. Results for a “Mission to Triton” study case show that use of such methods can allow to determine intervals of initial osculating orbital elements leading to relatively long term stable orbits. They prove to overcome results from the literature when a rigorous optimization approach (*i.e.*, reduction of the search space, global optimization, local optimization) is applied. [View Full Paper]

AAS 11 – 622

Optimal Transfer and Science Orbit Design in the Proximity of Small Bodies

Christopher J. Scott and **Martin T. Ozimek**, The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

This study details a robust and systematic approach for generating science orbits connected by fuel optimal transfers in the small body regime. The Clohessey-Wiltshire equations provide an analytical means to globally interpret the design space allowing a designer to quickly investigate families of science orbits and obtain closed-form optimal transfer. Solutions are refined with multiple shooting and nonlinear programming to transition the results into Hill’s equations, and finally, a high-fidelity ephemeris model. The final result is an accurate solution retaining the initial design characteristics with the potential for further fuel savings that are available from exploiting the high-fidelity perturbations. [View Full Paper]

AAS 11 – 623

Preliminary Analysis of Ballistic Trajectories to Uranus Using Gravity-Assists From Venus, Earth, Mars, Jupiter, and Saturn

Christopher M. Spreen, **Michael J. Mueterthies** and **James M. Longuski**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Kevin W. Kloster**, The Aerospace Corporation, El Segundo, California, U.S.A.

The goal of this paper is to investigate trajectories to Uranus for launch between the years 2020 and 2060. Ballistic gravity-assist trajectories are identified using both patched-conic techniques and a genetic algorithm. Classical trajectories, as well as less conventional trajectories, are considered and compared. Trajectories are constrained to flight times of 15 years or less. The best trajectories in terms of parameters such as time of flight, launch date, and ΔV cost are presented and discussed. [View Full Paper]

AAS 11 – 624
(Paper Withdrawn)

SESSION 26: LARGE SPACE STRUCTURES AND TETHERS
Chair: Dr. David Spencer, Pennsylvania State University

AAS 11 – 625

Analysis of the Out-of-Plane Dynamics of a Tether Sling Stationed on a Rotating Body

Steven G. Tragesser, Department of Mechanical and Aerospace Engineering, University of Colorado, Colorado Springs, Colorado, U.S.A.; **Luis G. Baars**, Braxton Technologies LLC, Colorado Springs, Colorado, U.S.A.

A previous study on the design of a tether sling has suggested that a facility can only be located at the poles of a moon or asteroid in order to align the angular momentum vectors of the moon and tether. This paper analyzes the out-of-plane motion induced from rotation of the body on which the facility is stationed. While significant out-of-plane oscillations are found in the open-loop behavior, the motion stabilizes about some finite amplitude. The mechanism for this stabilization is considered and the out-of-plane oscillation amplitude is characterized with respect to system parameters. Further stabilization of the system is shown to be possible by modulating the tether length, maintaining the reusable nature of the system. [View Full Paper]

AAS 11 – 626

Asteroid Diversion Using Tethers

M. J. Mashayekhi and **Arun K. Misra**, Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada

Potential Earth impact threats by asteroids or comets have generated a lot of interest in the study of Near Earth Object (NEO) diversion. Several methods to perturb the motion of an asteroid, ranging from the nuclear explosions to the use of solar sails and direct impact have been proposed in the literature. One of the effective non-nuclear techniques is the attachment of a tether and ballast to the asteroid to alter its trajectory. The effect of attachment of a tether and ballast mass to the asteroid and then cutting the tether at an appropriate time is investigated in this paper. The instant of cutting the tether is of crucial importance and is determined via the Simulated Annealing Optimization technique. [View Full Paper]

AAS 11 – 627

Attitude Controllability Study of an Underactuated Flexible Spacecraft

Dongxia Wang, **Yinghong Jia**, **Lei Jin** and **Jianfeng Yin**, School of Astronautics, Beihang University, Beijing, China

In order to provide a preconditional guide on designing the controller of under-actuated attitude control systems, this article analyzes the attitude controllability of an underactuated flexible spacecraft. The object is a central rigid body fixed with a flexible beam, actuated by two available thrusters. Firstly, an attitude dynamic model of the underactuated flexible spacecraft is established with thrusters, and the special orthogonal group (SO (3)) is deployed to describe the attitude motions. Secondly, neglecting the elastic deformations of the beam, the attitude controllability of the corresponding rigid body is analyzed based on the nonlinear analysis methods, and the sufficient condition for state controllability is obtained on the use of Lie Algebra Rank Condition (LARC). Thirdly, the impact of the flexible beam reckoned in, the system is simplified to the form of the state equation when we select the appropriate state variables. Then, through the controllability matrix judgment theorem, the sufficient and necessary condition for vibration controllability is derived, and furthermore a controllability index is proposed, to measure the degree of controllability. [View Full Paper]

AAS 11 – 628

(Paper Withdrawn)

AAS 11 – 629

Deployment Dynamics of a Large Solar Array Paddle

Takanori Iwata, Guidance and Control Group, Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, Japan; **Kiyoshi Fujii** and **Kazuro Matsumoto**, Thermal and Mechanical Systems Group, NEC TOSHIBA Space Systems, Fuchu, Tokyo, Japan

On January 24, 2006, the Advanced Land Observing Satellite (ALOS) successfully deployed its large solar array paddle on orbit. This solar array paddle is one of the largest single-wing paddles and accomplished the largest passive deployment of a rigid multiple panel paddle. This paper describes a design optimization for the ALOS' paddle deployment with various practical constraints such as deployment time and latch torque, and presents ground verification results including a series of deployment analyses and deployment tests. The effect of attitude motion on the deployment was assessed, and deployment robustness analyses assuming off-nominal conditions were performed to determine margins and identify critical failures. Flight data, including the paddle's telemetries, attitude and orbit control systems' telemetries, and monitor camera images were analyzed to correlate them with the pre-flight analyses. [View Full Paper]

AAS 11 – 630

Dynamics of a Moon-Anchored Tether with Variable Length

Aleksandr A. Burov and **Ivan I. Kosenko**, Dorodnitsyn Computing Center, Russian Academy of Sciences, Moscow, Russia; **Anna D. Guerman**, Centre for Aerospace Science and Technologies, University of Beira Interior, Covilha, Portugal

We consider the problem of motion of a mechanical system formed by the Earth, the Moon, and the space station connected to the Moon by an non-stretched tether of variable length. Supposing that the lunar orbit is elliptical, we find some classes of particular solutions for the equations of motion, analyze their stability, and study regular and chaotic dynamics of this system. [View Full Paper]

AAS 11 – 631

Effects of J_2 Perturbations on Multi–Tethered Satellite Formations

Giulio Avanzini, Università del Salento, Facoltà di Ingegneria Industriale, Brindisi, Italy; **Manrico Fedi**, Universitat Politècnica de Catalunya, Escola Politècnica Superior de Castelldefels, Catalonia, Spain

The paper discusses the relevance of J_2 effects induced by Earth's oblateness on a tethered formation, when a massive cable model is included in the dynamic analysis of a multi–tethered satellite formation. The formations examined in this study are Hub–And–Spoke (HAS) and Closed–Hub–And–Spoke (CHAS) configurations for in–plane and Eart–facing spin planes. Some configurations present a cluster with deputies affected differently by the J_2 potential depending on their initial position with respect to the orbital plane. The differences in stability, elongation of tethers and shape of the formations under the J_2 potential are compared with those in absence of the perturbation, in order to evaluate the relevance of the J_2 effect for the various configurations considered. [View Full Paper]

AAS 11 – 632

Analysis of a Tethered Coulomb Structure Applied to Close Proximity Situational Awareness

Carl R. Seubert, **Stephen Panosian** and **Hanspeter Schaub**, Aerospace Engineering Sciences Department, University of Colorado, Boulder, Colorado, U.S.A.

A unique tether application for situational awareness at geosynchronous altitudes is investigated. The relative dynamics between a small sensor platform tethered to a large host-spacecraft is examined. Charging both craft to |30| kV holds the relative dynamics fixed in the presence of gravitational and solar radiation forces. Numerical simulations illustrate the use of multiple tether connections increases the stiffness and allows 10 m separated craft to yield relative shape variations less than 50 mm in translation and 5 degrees in attitude. It is also shown that in nominal plasma conditions less than 20 W of power along with only grams of propellant are required to maintain spacecraft potentials. [View Full Paper]

AAS 11 – 633

Orbit Control Method for Solar Sail Demonstrator IKAROS via Spin Rate Control

Yuya Mimasu, Japan Aerospace Exploration Agency (JAXA), Sagamihara, Kanagawa, Japan; **Tomohiro Yamaguchi**, Department of Space and Astronautical Science, The Graduate University for Advanced Studies, Sagamihara, Kanagawa, Japan; **Masaki Nakamiya**, **Ryu Funase**, **Takanao Saiki**, **Yuichi Tsuda**, **Osamu Mori** and **Jun'ichiro Kawaguchi**, Japan Aerospace Exploration Agency (JAXA), Sagamihara, Kanagawa, Japan

It is well known that the thrust force of the solar sail due to the solar radiation pressure is changed by the orientation of the sail with respect to the Sun direction. Therefore, the orbit of the solar sail can be controlled by changing the attitude of the spacecraft. In this study, we consider the spinning solar power sail IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun), which succeeded to become the world's first flight solar sail in orbit. The IKAROS attitude, i.e. The spin-axis direction is nominally controlled by the rhumb-line control method. By utilizing the solar radiation pressure (SRP) torque, however, we are able to change the direction of the spin-axis only by controlling its spin rate. This is because the spin axis direction relates to the balance between the angular momentum of spinning and the SRP torque. Thus, we can control the solar sail's orbit by controlling the spin rate. The main objective in this study is to construct the orbit control strategy of the spinning solar sail via the spin rate control. [View Full Paper]

SESSION 27: OPTIMAL CONTROL
Chair: Dr. Rao Vadali, Texas A&M University

AAS 11 – 634

A Dynamic-Static Mesh Refinement Strategy for Solving Optimal Control Problems

Camila C. Françolin, **Michael A. Patterson** and **Anil V. Rao**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.

A mesh refinement strategy for solving optimal control problems is presented. The refinement strategy consists of a dynamic and a static component that run sequentially. The dynamic refinement component is run using a coarse global mesh and attempts to capture non-smoothness in the state and control and discontinuities in the control through the analysis of active path constraints. Consecutively, the static component of the refinement improves on the accuracy of the solution up to a user-specified tolerance by increasing the degree of the approximating polynomial or breaking up the problem into an increasing number of intervals. Two examples which contain path constraints in the control and the state were investigated and show that this method is effective in capturing discontinuities, giving greater solution accuracies. [View Full Paper]

AAS 11 – 635

A Minimum ΔV Orbit Maintenance Strategy for Low-Altitude Missions Using Burn Parameter Optimization

Aaron J. Brown, Flight Dynamics Division, NASA Johnson Space Center, Houston, Texas, U.S.A.

Orbit maintenance is the series of burns performed during a mission to ensure the orbit satisfies mission constraints. Low-altitude missions often require non-trivial orbit maintenance ΔV due to sizable orbital perturbations and minimum altitude thresholds. A strategy is presented for minimizing this ΔV using impulsive burn parameter optimization. An initial estimate for the burn parameters is generated by considering a feasible solution to the orbit maintenance problem. An low-lunar orbit example demonstrates the ΔV savings from the feasible solution to the optimal solution. The strategy's extensibility to more complex missions is discussed, as well as the limitations of its use.
[View Full Paper]

AAS 11 – 636
(Paper Withdrawn)

AAS 11 – 637

An Exploration of Fuel Optimal Two-Impulse Transfers to Cyclers in the Earth-Moon System

Saghar Hosseini Sianaki and **Benjamin F. Villac**, Department of Mechanical and Aerospace Engineering, University of California, Irvine, California, U.S.A.

This paper explores the optimum two-impulse transfer problem between a low Earth orbit and sample cycler orbits in the framework of the circular restricted three-body framework, emphasizing the optimization strategy. Cyclers are those type of periodic orbits that encounter both the Earth and the Moon periodically. Cyclers have gained recent interest as baseline orbits for several Earth-Moon mission concepts. In this paper we show that a direct application of Lambert initial guess may not be adequate for these problems, and a two-step process is investigated to improve upon the range of boundary conditions where convergence is reached. The first step consists of finding feasible trajectories with a given transfer time. Here two methods are investigated: the use of a shooting method from a Lambert initial guess, or smooth deformation of the dynamics from a Lambert solution using continuation methods. The second step optimizes the impulse over transfer time, which thus results in the minimum impulse transfer for fixed end points. Contour maps of optimal impulses in the phase space of departure and arrival points are then computed to summarize the results and show the limitation of the method. In particular, the direct optimization fails to converge for most boundary conditions, while the continuation from Lambert initial guess do not capture most Moon gravity assists transfers. Lambert solutions, however, are seen as providing a good approximation to the transfer cost, albeit not the velocity directions. [View Full Paper]

AAS 11 – 638
(Paper Withdrawn)

AAS 11 – 639

Experimental Investigations of Trajectory Guidance and Control for Differential Games

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The feedback solutions of Pursuit-Evasion games are of interest for formulating optimal strategies for the players in the game. In this paper feedback solution for a one pursuer and one evader zero-sum game is implemented on planar robots. The solution strategy exploits the differentially flat characteristic of robot models. The feedback strategy is demonstrated on hardware in real time using iRobot Create platforms. The effects of network latency and hardware limitations such as control bounds are studied. Results presented show the extent to which network latency and measurement noise affect the outcome of the game. [View Full Paper]

AAS 11 – 640

Exploiting Sparsity in Direct Collocation Pseudospectral Methods for Solving Optimal Control Problems

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In a direct collocation pseudospectral method, a continuous-time optimal control problem is transcribed to a finite-dimensional nonlinear programming problem. Solving this nonlinear programming problem as efficiently as possible requires that sparsity at both the first and second-derivative levels be exploited. In this paper a computationally efficient method is developed for computing the first and second derivatives of the nonlinear programming problem functions arising from a pseudospectral discretization of a continuous-time optimal control problem. Specifically, in this paper expressions are derived for the objective function gradient, constraint Jacobian, and Lagrangian Hessian arising from the previously developed Radau pseudospectral method. It is shown that the computation of these derivative functions can be reduced to computing the first and second derivatives of the functions in the continuous-time optimal control problem. As a result, the method derived in this paper reduces significantly the amount of computation required to obtain the first and second derivatives required by a nonlinear programming problem solver. The approach derived in this paper is demonstrated on an example, where it is found that significant computational benefits are obtained when compared against direct differentiation of the nonlinear programming problem functions. The approach developed in this paper improves the computational efficiency of solving nonlinear programming problems arising from pseudospectral discretizations of continuous-time optimal control problems. [View Full Paper]

AAS 11 – 641

Optimal Cooperative Deployment of a Two-Satellite Formation into a Highly Elliptic Orbit

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An indirect procedure to optimize the deployment of a two-spacecraft formation into a highly elliptic orbit is presented. The necessary conditions for the optimality are fully derived; a peculiar shooting technique, based on the Newton method, is described. An exhaustive numerical analysis is carried out considering the two-body Keplerian model; some results, taking the Lunisolar perturbation and the Earth Asphericity into account, are also presented. [View Full Paper]

AAS 11 – 642

Optimal Nonlinear Feedback Control for Control Constraints Problems with Terminal Constraints: An SDRE Approach

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Optimal feedback control strategies are extremely important for practical systems. In general, it is not easy to find feedback control strategies for nonlinear systems especially in the presence of control constraints. State dependent Riccati equation technique has been applied to obtain feedback control for the free final time problems with or without control constraints. In this paper, the use of this technique for fixed time problems with active control constraints and fixed final states is investigated.
[View Full Paper]

AAS 11 – 643

Spacecraft Proximity Maneuver Guidance Based on Inverse Dynamic and Sequential Gradient-Restoration Algorithm

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In this work the inverse dynamic in the virtual domain technique is coupled with the sequential gradient-restoration algorithm to generate, in real-time, suboptimal trajectories for close proximity maneuvers between a chaser and a moving non-cooperative target. The inverse dynamic in the virtual domain technique allow a simple analytical description of the prototype trajectory, on the other hand, the fast convergence performances of the sequential gradient-restoration algorithm guarantee a quick computation of the near-optimal solution trajectory. This method is implemented to an in-plane case in which a chaser spacecraft docks with a target spacecraft that is independently rotating. Both minimum fuel and minimum energy optimization criteria are considered. Exhaustive sets of simulations have proven the suitability of the presented approach.
[View Full Paper]

SESSION 28: RENDEZVOUS
Chair: Dr. Thomas Lovell, Air Force Research Laboratory

AAS 11 – 644

A Comparison of Fixed-Terminal Direction Guidance Laws for Spacecraft Rendezvous

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This work examines and compares two fixed-terminal direction guidance laws to rendezvous with a target in circular orbit. Both laws exactly satisfy the constraint. The first algorithm is based on the optimization of a quadratic performance index. The second algorithm has as many constraints as degrees of freedom and is the guidance law utilized by the Space Shuttle. Similarities and differences between the two approaches are discussed and numerical simulations are presented. [View Full Paper]

AAS 11 – 645

A Quadratically-Constrained LQR Approach for Finite-Thrust Orbital Rendezvous with Collision Avoidance

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This paper focuses on the design of a quadratically-constrained Linear-Quadratic Regulator for finite-thrust orbital rendezvous. The original Linear-Quadratic optimal control problem is subject to maximum thrust magnitude and quadratic collision avoidance constraints. Thrust arcs are approximated by impulsive velocity increments and the Yamanaka-Ankersen transition matrix propagates the state vector. An explicit closed-loop solution is obtained by performing high-order series expansions of the HJB equation on sub-regions of the state-space associated with specific sets of active constraints. A rendezvous in an elliptical orbit is considered to demonstrate the application of this method. [View Full Paper]

AAS 11 – 646
(Paper Withdrawn)

AAS 11 – 647

Asteroid Precision Landing via Multiple Sliding Surfaces Guidance Techniques

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Autonomous close proximity operations (hovering, landing) in the low-gravity environment exhibited by asteroids are particularly challenging. A novel nonlinear landing guidance scheme has been developed for spacecrafts that are required to execute autonomous closed-loop guidance to a designated point on the asteroid surface. Based on High Order Sliding Mode control theory, the proposed Multiple Sliding Surface Guidance (MSSG) algorithm has been designed to take advantage of the ability of the system to reach the sliding surface in a finite time. High control activity typical of sliding control design is avoided resulting in a guidance law that is robust against unmodeled yet bounded perturbations. The proposed MSSG does not require any off-line trajectory generation and therefore it is flexible enough to target a large variety of points on the surface without the need of ground-based trajectory analysis. The global stability of the proposed guidance algorithm is proven using a Lyapunov-based approach. The behavior of the MSSG-based class of asteroid landing trajectories is investigated via a parametric analysis and a full set of Monte Carlo simulations in realistic landing scenarios. Based on such results, the MSSG algorithm is demonstrated to be very accurate and flexible. The proposed scheme is suitable for onboard implementation and deployment for asteroid landing and close proximity operations. [View Full Paper]

AAS 11 – 648

(Paper Withdrawn)

AAS 11 – 649

HTV Relative Approach Performance Evaluation Based on On-Orbit Rendezvous Flight Result

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The H-II Transfer Vehicle (HTV), as an unmanned vehicle, conducts automatic rendezvous flight to the manned space station, therefore strict safety requirements are applied. During the HTV final approach along the R-bar, the HTV GN&C system continuously controls relative position so that its trajectory must keep within predefined approach corridor. For final robotic capture, fine position hold and attitude control performance are required when the HTV reaches about 10 m below the space station. This paper presents the HTV GN&C design for R-bar approach, analysis and test results, and the HTV 1st and 2nd flight on-orbit performance evaluation. [View Full Paper]

AAS 11 – 650

Multi-Maneuver Clohessy-Wiltshire Targeting

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A non-iterative method is presented for targeting a rendezvous scenario that includes a sequence of maneuvers and relative constraints. This method is referred to as Multi-Maneuver Clohessy-Wiltshire Targeting (MM_CW_TGT). When a single maneuver is targeted to a single relative position, the classic CW targeting solution is obtained. The MM_CW_TGT method involves manipulation of the CW state transition matrix to form a linear system. Solution of the linear system includes the straight-forward inverse of a square matrix. Example solutions are presented for several rendezvous scenarios to illustrate the utility of the method. [View Full Paper]

AAS 11 – 651

Optimal Finite-Thrust Rendezvous Trajectories Found via Particle Swarm Algorithm

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The particle swarm optimization technique is a population-based stochastic method developed in recent years and successfully applied in several fields of research. It represents a very intuitive (and easy to program) methodology for global optimization, inspired by the behavior of bird flocks while searching for food. The particle swarm optimization technique attempts to take advantage of the mechanism of information sharing that affects the overall behavior of a swarm, with the intent of determining the optimal values of the unknown parameters of the problem under consideration. This research applies the technique to determining optimal continuous-thrust rendezvous trajectories in a rotating Euler-Hill frame. Hamiltonian methods are employed to translate the related optimal control problems into parameter optimization problems. Thus the parameters sought by the swarming algorithm are primarily the initial values of the costates and the final time. The algorithm at hand is extremely easy to program. Nevertheless, it proves to be effective, reliable, and numerically accurate in solving the rendezvous optimization problems considered in this work. [View Full Paper]

AAS 11 – 652

Out-of-Plane Post-Escape Strategy for the ATV

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Laurent Arzel and **Emilio De Pasquale**, ATV Operations Division, ESA Project ATC-CC, Toulouse, France

While rendezvousing with its target, the chaser might trigger an escape maneuver to safely fly away from the target. A post-escape strategy is then performed to re-initiate the rendezvous. Standard strategies are in-plane: if the rendezvous is along minus Vbar, the chaser first flies below and then above the target. A new approach is proposed in this paper: by combining eccentricity vector, inclination vector and semi-major axis deviations, it is possible to fly around the target in a helix trajectory. This new approach is applied to the ATV with the ISS. It looks promising in terms of DeltaV cost reduction and safety margins improvement. [View Full Paper]

AAS 11 – 653

Precise Guidance and Landing Strategy of Space Probe by Using Multiple Markers in Asteroid Exploration Mission

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This paper proposes a novel strategy for a space probe to descent and land on the asteroid surface with high accuracy of a few meters by utilizing several artificial markers deployed from the probe. Results of a numerical experiment indicated that the proposed method showed higher performance than conventional one. It will allow us to guide the probe with high mobility to the desired points such as small craters, which will be of great significance for understanding local geology and geography of the asteroid, or avoiding boulders and too rough regions. [View Full Paper]

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