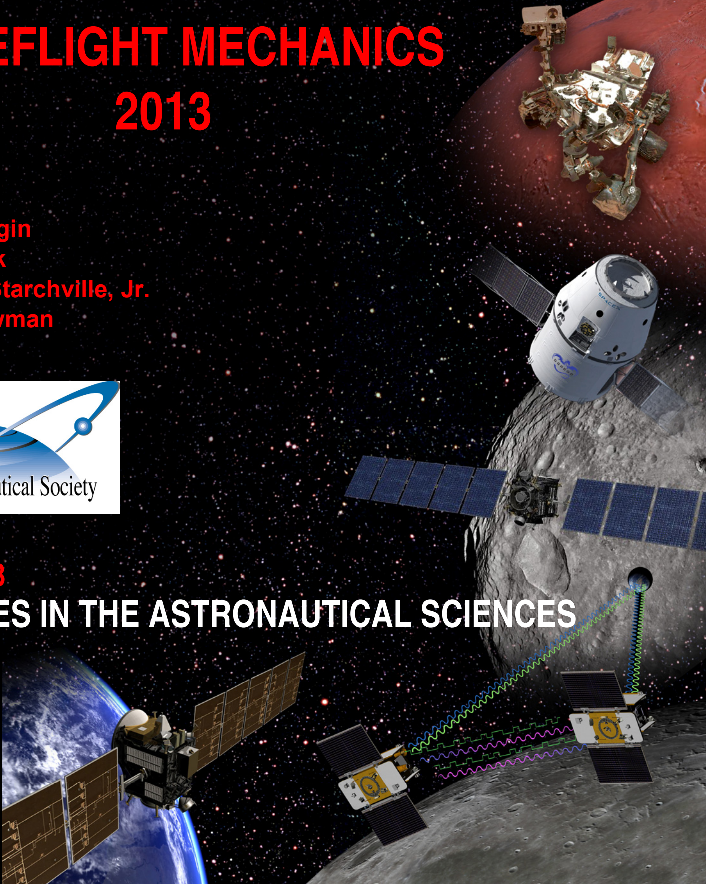
SPACEFLIGHT MECHANICS 2013

Edited by
Sergei Tanygin
Ryan S. Park
Thomas F. Starchville, Jr.
Lauri K. Newman

American Astronautical Society

Volume 148
ADVANCES IN THE ASTRONAUTICAL SCIENCES



SPACEFLIGHT MECHANICS 2013

Front Cover Illustration:

Top Right: The Mars Science laboratory Curiosity Rover successfully landed in Gale Crater on August 6, 2012. Credit: NASA /Jet Propulsion Laboratory.
Upper Middle: The Dragon spacecraft became the first commercial vehicle in history to successfully attach to the International Space Station May 25, 2012. Credit: Space Exploration Technologies (SpaceX).
Lower Middle: The Dawn Spacecraft enters orbit about asteroid Vesta on July 16, 2011. Credit: Orbital Sciences Corporation and NASA/Jet Propulsion Laboratory, California Institute of Technology.
Lower Right: GRAIL-A and GRAIL-B spacecraft, which entered lunar orbit on December 31, 2011 and January 1, 2012, fly in formation above the moon. Credit: Lockheed Martin and NASA/Jet Propulsion Laboratory, California Institute of Technology.
Lower Left: The Dawn Spacecraft launch took place September 27, 2007. Credit: Orbital Sciences Corporation and NASA/Jet Propulsion Laboratory, California Institute of Technology.

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FOREWORD

This volume is the twenty-third of a sequence of Spaceflight Mechanics volumes which are published as a part of *Advances in the Astronautical Sciences*. Several other sequences or subseries have been established in this series. Among them are: Astrodynamics (published for the AAS every second year), 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 or in microfiche form. The appendix at the end of Part IV of the hard copy volume lists proceedings available through the American Astronautical Society.

Spaceflight Mechanics 2013, Volume 148, Advances in the Astronautical Sciences, consists of four parts totaling about 4,200 pages, plus a CD ROM which contains all the available papers in digital format. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume. A chronological index and an author index are appended to the fourth part of the volume.

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

We commend the general chairs, technical chairs, session chairs and the other participants for their role in making the conference such a success. We would also like to thank those who assisted in organizational planning, registration and numerous other functions required for a successful conference.

The current proceedings are valuable to keep 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. This current material should be a boon to aerospace specialists.

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

Spaceflight Mechanics 2013 appears as Volume 148, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the 23rd AAS/AIAA Space Flight Mechanics Meeting 2013.

Spaceflight Mechanics 2012, Volume 143, *Advances in the Astronautical Sciences*, Eds. J.V. McAdams et al., 2,612p., three parts, plus a CD ROM supplement.

Spaceflight Mechanics 2011, Volume 140, *Advances in the Astronautical Sciences*, Eds. M.K. Jah et al., 2622p., three parts, plus a CD ROM supplement.

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Spaceflight Mechanics 2007, Volume 127, *Advances in the Astronautical Sciences*, Eds. M.R. Akella et al., 2230p., two parts, plus a CD ROM supplement.

Spaceflight Mechanics 2006, Volume 124, *Advances in the Astronautical Sciences*, Eds. S.R. Vadali et al., 2282p., two parts, plus a CD ROM supplement.

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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 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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Astrodynamics 2011, Volume 142, Advances in the Astronautical Sciences, Eds. H. Schaub et al., 3916p, four parts plus a CD ROM Supplement.

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Astrodynamics 2005, Volume 123, *Advances in the Astronautical Sciences*, Eds. B.G. Williams et al., 2878p, three parts plus a CD ROM Supplement.

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Astrodynamics 2001, Volume 109, *Advances in the Astronautical Sciences*, Eds. D.B. Spencer et al., 2592p, three parts.

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Astrodynamics 1983, Volume 54, *Advances in the Astronautical Sciences*, Eds. G.T. Tseng et al., 1370p, two parts; Microfiche Suppl., 41 papers (Vol. 45 *AAS Microfiche Series*)

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Astrodynamics 1979, Volume 40, *Advances in the Astronautical Sciences*, Eds. P.A. Penzo et al., 996p, two parts; Microfiche Suppl., 27 papers (Vol. 32 *AAS Microfiche Series*)

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Astrodynamics 1973, Volume 21, *AAS Microfiche Series*, 44 papers

Astrodynamics 1971, Volume 20, *AAS Microfiche Series*, 91 papers

All of these proceedings are available from Univelt, Inc., P.O. Box 28130, San Diego, California 92198 (Web Site: http://www.univelt.com), publishers for the AAS.

Robert H. Jacobs, Series Editor

PREFACE

The 23rd Space Flight Mechanics Meeting was held at the Kauai Marriott Resort, Kauai, Hawaii, February 10-14, 2013. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Technical Committee (TC) and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics TC. The 241 people registered for the meeting included 80 students as well as engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

There were 233 technical papers presented in 28 sessions on topics related to space-flight mechanics and astrodynamics. The five special sessions on Mars Science Laboratory, Dawn and GRAIL missions were well received and strongly attended.

An award ceremony and Dirk Brouwer Award lecture were held after the completion of all sessions late on Tuesday afternoon, February 12. Attendees were treated to a presentation entitled "The Mechanics of Exploring Asteroids" by Brouwer Award winner Prof. Daniel Scheeres.

The editors extend their gratitude to the Session Chairs who made this meeting successful: Ossama Abdelkhalik, Maruthi Akella, Rodney Anderson, Shyam Bhaskaran, Steve Broschart, Stefano Casotto, Paul Cefola, David Dunham, Thomas Eller, Michael Gabor, Yanping Guo, Eric Gustafson, Marcus Holzinger, Kathleen Howell, T. S. Kelso, Gerhard Kruizinga, Don Mackison, Tomas Martin-Mur, Robert Melton, Ryan Russell, Hanspeter Schaub, Daniel Scheeres, John Seago, Jon Sims, David Spencer, Kenneth Williams, and Renato Zanetti. Our gratitude also goes to AAS Headquarters staff members Jim Kirkpatrick and Diane Thompson for their support and assistance.

We would also like to express our thanks to Analytical Graphics, Inc. for the cover design and sponsorship of the conference programs.

Dr. Sergei Tanygin
Analytical Graphics, Inc.
AAS Technical Chair

Dr. Thomas F. Starchville, Jr.
The Aerospace Corporation
AAS General Chair

Dr. Ryan S. Park
Jet Propulsion Laboratory
AIAA Technical Chair

Lauri K. Newman
NASA Goddard Space Flight Center
AIAA General Chair

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SESSION 1: ORBIT DETERMINATION AND ESTIMATION THEORY I
Chair: Dr. Michael Gabor, TASC

AAS 13 – 200
Nonlinear Filtering Based on Taylor Differential Algebra

Roberto Armellin, Monica Valli, Pierluigi Di Lizia and Michèle R. Lavagna, Aerospace Engineering Department, Politecnico di Milano, Milan, Italy;
Renato Zanetti, Vehicle Dynamics and Control, The Charles Stark Draper Laboratory, Houston, Texas, U.S.A.

The problem of nonlinear filtering represents a crucial issue in celestial mechanics. In this paper a high-order filter based on differential algebra is presented. The proposed filtering algorithm is based on nonlinear mapping of statistics and a linear update scheme, in which only the probability density function of the measurement errors are constrained to be Gaussian. No hypothesis on the state probability density function is made. The case of an Earth-orbiting spacecraft in a two-body problem frame is considered as an example to demonstrate the general feature and performance of the filter. A comparison with the extended and unscented Kalman filters is also included.
[View Full Paper]

AAS 13 – 201
VLS Chebyshev Interpolation

James R Wright and **William Chuba**, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

The variable lag smoother (VLS) performs optimal sequential orbit determination from spacecraft sensor measurements, where smoothing at fixed epochs is performed simultaneously with forward filtering. For low earth orbit (LEO), smoothed VLS spacecraft orbit estimates are created at fixed epochs with uniform one-minute granularity to enable sufficiently accurate *Lagrange* interpolation. But for *Lagrange* interpolation, computer execution is unacceptably slow due to computation of many smoothed VLS orbit estimates at fixed epochs. This problem is solved using Chebyshev interpolation. We quantify the relative reduction in computer wall time throughput due to reduced number of VLS smoothed estimates required for Chebyshev interpolation as compared to Lagrange interpolation. Chebyshev interpolation works on a non-uniform time grid with far fewer interpolation points than is required for Lagrange interpolation.
[View Full Paper]

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(Paper Withdrawn)

AAS 13 – 203

Analytic Characterization of Measurement Uncertainty and Initial Orbit Determination on Orbital Element Uncertainty and Correlation

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

This paper applies the transformation of variables technique to analytically map measurement domain probability density functions to nonlinearly related, but commonly utilized state domains for space surveillance. For full state construction, the Herrick-Gibbs initial orbit determination routine is employed with the transformation of variables technique applied to assess state uncertainty and correlation resulting from the application of the routine for objects residing in and transiting low Earth orbit. Results are reported for the Cartesian, osculating and mean orbital element domains and compared against Monte Carlo simulation results and the commonly utilized similarity transformation. [View Full Paper]

AAS 13 – 204

Statistical Tests for Gaussian Mean and Covariance in Orbit Propagation

Laura S. Henderson, Mechanical and Aerospace Engineering Department, University of Texas at Arlington, Texas, U.S.A.; **Vincent Coppola**, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

We are interested in determining the duration that a nominal orbit trajectory's propagated mean and covariance well-approximate the statistics of an ensemble, where the ensemble is propagated using the fully nonlinear dynamics. Two standard statistical tests are performed to determine the time at which the ensemble statistics are no longer well-approximated by the nominal. The initial covariance is chosen from a simulated orbit determination solution, so that it represents typical orbit uncertainty experienced in practice. Several examples, from different orbit regimes and represented in different coordinates, it will be shown to be a guide for orbit determination practitioners.
[View Full Paper]

AAS 13 – 205
(Paper Withdrawn)

AAS 13 – 206

Improving Orbit Determination With Non-Cannonball Solar Radiation Pressure Models

Jay McMahon, Aerospace Engineering Sciences Department, University of Colorado, Boulder, Colorado, U.S.A.

This paper investigated the weaknesses of using the cannonball model to represent the solar radiation pressure force on an object in an orbit determination filter. These weaknesses are rooted in the fact that the cannonball model is not a good representation of the true solar radiation pressure force acting on an object. Using unrealistic dynamics in a filter causes four distinct issues: first, the state estimate will be incorrect; second, predictions made from this estimate, with the improper force model, will be very inaccurate; third, the covariance reported by the filter will be unrealistic; and fourth, long and/or dense arcs of data can't be fit. These issues are illustrated through numerical examples of one of the GRACE satellites in low-Earth orbit, and more drastically for a piece of high area-to-mass ratio debris in a near GEO orbit.

The results shown in this paper present a strong case that the cannonball model is not sufficient for accurately tracking HAMR debris objects. An improved SRP model, however, would greatly improve catalog maintenance issues. An accurate force model allows for precise orbit determination with realistic covariance bounds, and most importantly allows these estimates to be propagated such that the covariance realistically contains the object in the future. This is a necessity for proper track correlation and object identification. Finally, an accurate force model allows longer and more dense arcs of data to be used to maintain catalog entries. [View Full Paper]

AAS 13 – 207

Interplanetary Departure Stage Navigation By Means of Liaison Orbit Determination Architecture

Ryan M. McGranaghan, **Jason M. Leonard**, **Kohei Fujimoto**, **Jeffrey S. Parker** and **George H. Born**, University of Colorado, Boulder, Colorado, U.S.A.;
Rodney L. Anderson, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Autonomous orbit determination for departure stages of interplanetary trajectories is conducted by means of realistic radiometric observations between the departing spacecraft and a satellite orbiting the first lunar libration point. Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) is used to estimate the orbit solution. This paper uses high-fidelity simulations to explore the utilization of LiAISON in providing improved accuracy for interplanetary departure missions. The use of autonomous navigation to supplement current techniques for interplanetary spacecraft is assessed using comparisons with ground-based navigation. Results from simulations including the Mars Science Laboratory, Mars Exploration Rover, and Cassini are presented. It is shown that observations from a dedicated LiAISON navigation satellite could be used to supplement ground-based measurements and significantly improve tracking performance. [View Full Paper]

AAS 13 – 208

Unscented Kalman Filter Robustness Assessment for Orbit Determination Using GPS Signals

Paula C. P. M. Pardal and **R. V. Moraes**, ICT, UNIFESP, São José dos Campos, SP, Brazil; **Helio K. Kuga**, DMC, INPE, São José dos Campos, SP, Brazil

The purpose of this work is to evaluate the nonlinear unscented Kalman filter (UKF) for the satellite orbit determination problem, using GPS measurements. The assessment is based on the robustness of the filter. The main subjects for the evaluation are convergence speed and dynamical model complexity. Such assessment is based on comparing the UKF results with the extended Kalman filter (EKF) results in the solution of the same problem. Based on the analysis of such criteria, the advantages and drawbacks of the implementations are presented. In this work, the orbit of an artificial satellite is determined using real data from the Global Positioning System (GPS) receivers. In this orbit determination problem the focus is to analyze UKF convergence behavior using different sampling rates for the GPS signals, where scattering of measurements will be taken into account. A second aim is to evaluate how the dynamical model complexity affects the performance of the estimators in such adverse situation. Therefore, a performance comparison between EKF and UKF is justified. In this work, the standard differential equations describing the orbital motion and the GPS measurements equations used in the EKF algorithm need to be placed in a suitable form. They are adapted for the unscented transformation application, so that the UKF algorithm is also used for estimating the orbital state. After solving the real time satellite orbit determination problem using actual GPS measurements, through both the EKF and the UKF algorithms, the results obtained are compared in computational terms such as complexity, convergence, and accuracy. [View Full Paper]

AAS 13 – 209

Real-Time Orbit Determination for Lunar And Planetary Missions

Ryo Nakamura and **Hitoshi Ikeda**, Japan Aerospace Exploration Agency, Tsukuba-shi, Ibaraki, Japan; **Chikako Hirose**, Japan Aerospace Exploration Agency, Sagamihara-shi, Kanagawa, Japan; **Ken Nakajima**, Mitsubishi Space Software Co., Ltd. Tsukuba-shi, Ibaraki, Japan,

We develop a tool for real-time orbit determination for lunar and planetary missions, in which two-way tracking data acquired by one ground station is available. The Extended Kalman Filter (EKF) is widely used for nonlinear estimation and real-time orbit determination. The estimation filter based on EKF, however, may become unstable and sometimes diverge, when applied to a strong nonlinear system or a system with not-enough measurements. We implement an improved filter, called the Unscented Kalman Filter (UKF), for the tool. The UKF has an advantage over the EKF in that they approximate the mean and covariance of state more accurately than EKF. The developed tool is evaluated through the orbit determination simulations during orbit insertion maneuvers of Japanese Venus Climate Orbiter "Akatsuki" and SELenological and ENgineering Explorer "Kaguya". The simulation results indicate that the tool works well and the UKF is superior to the EKF in terms of both accuracy and stability of real-time orbit determination. [View Full Paper]

AAS 13 – 285

GOCE Fully-Dynamic Precise Orbit Recovery

Francesco Gini and **Francesca Panzetta**, Centro Interdipartimentale di Studi e Attività Spaziali (CISAS), Università degli Studi di Padova, Padova, Italy;
Massimo Bardella and **Stefano Casotto**, Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Padova, Italy

GOCE was launched in 2009 at 250 km altitude to recover Earth's static gravity field. As part of the GOCE-Italy project, we carried out GPS-based, fully-dynamic POD of GOCE for daily arcs covering about 500 days (November 1, 2009 – May 31, 2011). Two sequences were defined and implemented with the software NAPEOS (ESA/ESOC). The first sequence performs the POD task for 30-hours daily arcs, leading to 6 hours overlap between subsequent days, while the second sequence performs the same task for 24-hours daily arcs. Both the sequences were built using the official kinematic Precise Scientific Orbits (PSO) as a-priori orbits. The sequence with overlaps was used to process all the available data, while the second one was run only for those days where the overlaps were not possible or when the first sequence failed. The POD task was successfully performed for 99.4% of the total available days of data, and results show an average post-fit RMS of zero-difference phase measurements below 10 mm for 91.5% of the daily arcs. Most orbits compare to less than 6 cm 3D RMS with respect to the official kinematic PSO orbits and the overlapping arcs show an RMS of the distance of about 13 mm. [View Full Paper]

AAS 13 – 477

On the Expected Value of Sensed Data

James D. Turner and **Ahmad Bani Younes**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

A common task for all large-scale scientific and engineering undertakings is the development of sensing systems to gather data about the behavior of a physical system. To this end, many research efforts have been devoted to developing estimation algorithms for processing the sensed data for tasks such as data gathering and/or for providing control inputs for commanding the motions of the physical system. A common assumption is that the underlying uncertainty is Gaussian in nature. Unfortunately, for nonlinear systems, the assumed Gaussian behavior for the error models is not valid. Extended Kalman filtering provides a classical approach for handing nonlinear problem. At the heart of the estimation issue is the development of state projections that are based on a measurement of system inputs and output, which are driven by the dynamics and model and sensor uncertainty. Computationally intense Monte-Caro simulations often used to evaluate the expected spread in the uncertainty. Recent research by Turner, Bani Younes, Majji, and Junkins have explored an alternative estimation approach for handling model uncertainty that exploits the use of nonlinear tensor-based state transition tensors for propagating initial uncertainties. These advanced series-based approaches have demonstrated that nonlinear statistical models can be successfully modeled. This work develops an estimation model that retains the full nonlinear model for the plant and sensor, process, noise, measurement noise, and initial condition uncertainty. An optimal gain matrix is computed by differentiating a series-based representation of the nonlinear covariance matrix w.r.t. the gain matrix elements, leading to a Newton-like algorithm for differentially minimizing the instantaneous covariance matrix. This approach builds on the interpretation of the extended Kalman filter as a Gauss-Newton method. [View Full Paper]

SESSION 2: ATTITUDE DETERMINATION, DYNAMICS, AND CONTROL I
Chair: Dr. Renato Zanetti, The Charles Stark Draper Laboratory

AAS 13 – 211
(Paper Withdrawn)

AAS 13 – 212
(Paper Withdrawn)

AAS 13 – 213

Comparison of Multiple-Period and Higher Order Repetitive Control Used to Produce Robustness to Period Fluctuations

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

Repetitive control (RC) is a form of control that specifically aims to eliminate the effects of periodic disturbances using knowledge of the disturbance period. It has applications in spacecraft for eliminating disturbances to fine pointing equipment from slight imbalance in reaction wheels or CMG's. In this paper, a spacecraft laser pointing test bed is used for experiments. In some RC applications the period can fluctuate, or the assessment of the period is course due to sampling effects, or the error frequency peak from the disturbance is somewhat wide. In such cases there is a need for control methods that are robust to imprecise knowledge of the disturbance period. This paper evaluates a new method of addressing this problem, by using multiple period repetitive control (MPRC) and making the multiple periods identical. This approach is compared in numeric simulations to the existing method in the literature, higher order repetitive control (HORC) with negative weights. Experimental results will be reported in another publication. In addition, it is shown how to make several other control approaches address the same problem, including matched basis function repetitive control and model predictive control. Advantages and disadvantages of each approach are determined.
[View Full Paper]

AAS 13 – 214

Stability of Spinning Satellite Under Axial Thrust and Internal Mass Motion Including Damping

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Jozef C. van der Ha, Consultant, Deming, Washington, U.S.A.

The paper extends and clarifies the stability results for a spinning satellite under axial thrust in presence of internal damped mass motion. It is known that prolate and oblate satellite configurations can be stabilized by damped mass motion. Here, the stability boundaries are established by exploiting the properties of the complex characteristic equation and the results are interpreted in terms of the physical system parameters. When the thrust level is the only free parameter, both prolate and oblate satellites can be stabilized provided that the thrust is within a specified range. This result is in contrast to the well known maximum-axis rule for a free spinner where damping is always stabilizing (destabilizing) for an oblate (prolate) satellite. When adding a suitable spring-mass system, the minimum value of the spring constant required for stabilizing the configuration can be calculated. In practice, however, the damping may be too weak to be effective. Numerical illustrations are presented for the actual in-flight Ulysses parameters and for a fictitious oblate configuration. Finally, a new derivation of a previously established first integral for the undamped system is offered and its properties as a Lyapunov function are discussed. [View Full Paper]

AAS 13 – 215

(Paper Withdrawn)

AAS 13 – 216

Switching Angular Velocity Observer for Rigid-Body Attitude Stabilization and Tracking Control

Apurva A. Chunodkar and **Maruthi R. Akella**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.

This paper provides a new switching observer formulation to the classical problem of rigid body attitude tracking control in the absence of angular rate measurements. Exponential convergence of the state estimation errors is proven using a novel definition for the angular velocity estimation error through the use of this switching-type observer. The observer is independent of controller design. Further, the maximum number of switches required by the observer can be shown to be finite. A separation property type result for the attitude tracking problem is established, wherein a proportional-derivative controller utilizes angular velocity estimates from the proposed switching observer in the absence of actual angular rate measurements while ensuring almost global asymptotic stability for the overall closed-loop tracking error dynamics. [View Full Paper]

AAS 13 – 217

Modeling of 3D Slosh Motion for Spacecraft With Multiple Liquid Stores

Yunhwan Kim, School of Mechanical and Aerospace Engineering, Korea Aerospace University, Deogyang-gu, Goyang, Gyeonggi-do, South Korea;
Ja-Young Kang, Department of Aeronautical Science, Korea Aerospace University, Deogyang-gu, Goyang, Gyeonggi-do, South Korea

Most studies regarding the spacecraft attitude motion were involved with the rigid body dynamics with simple slosh model and very "few" dealt with three-dimensional slosh motion of liquid. Even though full nonlinear slosh model is adopted, solving simultaneous nonlinear equations of motions is troublesome. We develop equations of motion of a spacecraft which is equipped with a momentum wheel and two propellant storages. As equivalent mechanical models to describe the three dimensional 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. Based on the Moore-Penrose pseudo inverse technique, propellant equations of motion are decoupled and equations of motion for spacecraft and propellants are numerically solved to observe the effect of fuel slosh in multiple propellant tanks on the spacecraft attitude motion during maneuvers. [View Full Paper]

AAS 13 – 218

Fault Tolerant Attitude Control for Small Satellites By Using Single Gimbal Control Moment Gyros and Magnetic Torquers

Lei Jin and **Shijie Xu**, School of Astronautics, Beihang University, Haidian District, Beijing, P. R. China; **K. Khorasani**, Department of Electrical and Computer Engineering, Concordia University, Montreal, Quebec, Canada

A fault tolerant control scheme is proposed for attitude maneuver of a small satellite by using single gimbal control moment gyros (SGCMGs) and magnetic torquers (MTQs). First, the dynamic model of rigid spacecraft using SGCMGs and MTQs is established and the faults of SGCMGs are modeled as additive and multiplicative unknown dynamics. By designing a well-tuned Linear Extended State Observer (LESO), the dynamic uncertainties, external disturbances and the partial loss of SGCMGs effectiveness are estimated exactly and compensated actively in real time without knowing the accurate spacecraft model. Then, based on singular value decomposition theory, the command torque is decomposed and distributed to SGCMGs and MTQs respectively, and SGCMGs only need to output the torque component orthogonal to the singular direction when encountering singularity, ensuring the controllability of SGCMGs. By comparing with a conventional PD control method, the numerical simulations demonstrate that this scheme can tolerate potential SGCMGs faults and resolve the singularity problem, maintaining the desirable stability and performance of the satellite.
[View Full Paper]

AAS 13 – 219

Nonlinear Attitude Stability of a Spacecraft on a Stationary Orbit Around an Asteroid Subjected to Gravity Gradient Torque

Yue Wang and **Shijie Xu**, Department of Aerospace Engineering, School of Astronautics, Beihang University, Beijing, China

The classical problem of attitude stability in a central gravity field is generalized to that on a stationary orbit around a uniformly-rotating asteroid. This generalized problem is studied in the framework of geometric mechanics. Based on the natural symplectic structure, the non-canonical Hamiltonian structure of the problem is derived. The Poisson tensor, Casimir functions and equations of motion are obtained in a differential geometric method. The equilibrium of the equations of motion, i.e. the equilibrium attitude of the spacecraft, is determined from a global point of view. Nonlinear stability conditions of the equilibrium attitude are obtained with the energy-Casimir method. The nonlinear attitude stability is then investigated versus three parameters of the asteroid, including the ratio of the mean radius to the stationary orbital radius, the harmonic coefficients C_{20} and C_{22}. It is found that when the spacecraft is located on the intermediate-moment principal axis of the asteroid, the nonlinear stability domain can be totally different from the classical Lagrange region on a circular orbit in a central gravity field.
[View Full Paper]

AAS 13 – 480

Experimental Characterization of a Miniature Laser Rangefinder for Resident Space Object Imaging

Kristia Harris, **Ayham Baba**, **Joseph DiGregorio**, **Timothy Grande**, **Christian Castillo**, **Timothy Zuercher** and **Bogdan Udrea**, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.; **Michael V. Nayak**, Space Development and Test Directorate, Kirtland AFB, New Mexico, U.S.A.

ARAPAIMA is a proximity operations mission sponsored by the US Air Force Office of Scientific Research (AFOSR) and the Air Force Research Laboratory (AFRL) designed to perform the in-orbit demonstration of autonomous proximity operations and visible, infrared (IR) and three-dimensional imaging of Resident Space Objects (RSOs) from a nanosat platform. A miniature time-of-flight Laser Range Finder (LRF) similar to the FLIR MLR100 is proposed as a mission payload to generate point clouds of RSOs. This paper is focused on the use of experimental test data to characterize errors inherent within the MLR100. Results of the experiments and test data discussed here are directly applicable to characterizing the flight LRF, as well as constraining stochastic and laser beam pulse dilation error models. The models will be employed in mission imaging algorithms developed to parse LRF point clouds into recognizable RSO shapes. Experiments presented include the use of flat targets made of diverse materials, mounted on a rotating platform. Materials for the targets are representative of those typically used for satellite construction, such as aluminum alloy, Mylar, solar cells, and fine steel mesh. The angle of incidence with respect to the LRF receiver optical axis is varied from 0 to 45° such that the normal to its surface defines a plane containing the receiver optical axis. This simulates returns from various surfaces of an RSO as the ARAPAIMA nano-satellite flies around it. Measurements are taken at 5, 10 and 30m across lighting conditions that simulate daylight, eclipse and terminator transition. Results from all the tests, the experimental LRF error model, and additional characterization work on the MLR100 are discussed in light of their applicability to the ARAPAIMA space-based space situational awareness (SSA) mission. [View Full Paper]

AAS 13 – 483

Quaternion-Based Backstepping for Line-of-Sight Tracking of Satellites Using Only Magnetorquers

Deepti Kannapan, **Arun D. Mahindrakar** and **Sandipan Bandyopadhyay**, Indian Institute of Technology Madras, Chennai, India

A new strategy for the design of tracking control laws is presented for line-of-sight (LoS) pointing control of satellites that use only magnetorquers. This strategy makes use of the backstepping approach, and applies to satellites that require the LoS of a single instrument, such as a transmission antenna or camera, to be pointed at a given time, but not both simultaneously. Asymptotic stability of the desired trajectory is proved, provided the target pointing-direction lies outside some critical range. A control law so developed is numerically simulated for a nanosatellite mission scenario to demonstrate feasibility. [View Full Paper]

SESSION 3: TRAJECTORY OPTIMIZATION I
Chair: Dr. Thomas Eller, Astro USA, LLC

AAS 13 – 220

Loads Alleviation on European Launchers Using Wind Biased Trajectory Optimization

Benjamin Carpentier, **Benoit Mazellier** and **Amaya Espinosa-Ramos**, Launchers Directorate, CNES, Paris, France; **Pierre-Emmanuel Haensler**, ALTEN Technologies, Boulogne-Billancourt, France

In this paper, a first impact study of wind biasing techniques for trajectory optimization on European launchers is presented. Such techniques have been extensively studied and applied on US launchers since early 1960's, but European launchers' programs have never considered them up to now.

The implementation of wind biasing technique in the trajectory optimization process is first discussed. A benchmark representative of a typical small scale European launcher is then considered to assess pros and cons of trajectory optimization in front of seasonal mean or day-of-launch measured wind profiles. 6dof simulations are performed in front of a large number of wind profiles, and various parameters such as AoA and TVC deflection are analyzed.

A large improvement of AoA statistics, and consequently of loads seen by the launch vehicle, is demonstrated. This improvement is particularly important for a day-of-launch wind use, but with consequences on operations during launch chronology.

The work presented in this paper has been performed in the frame of CNES Launchers' Research and Technology program, between 2010 and 2012.
[View Full Paper]

AAS 13 – 221

Time-Optimal Trajectory Design for a Dual-Satellite Sailcraft Interstellar Mission With Probe Release

Xiangyuan Zeng, **Kyle T. Alfriend** and **Srinivas R. Vadali**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.;
Hexi Baoyin and **Shengping Gong**, Tsinghua University, Haidian, Beijing, China

In this paper, a time-optimal trajectory design for a novel dual-satellite sailcraft is presented to accomplish mid or far-term interstellar missions. The mission considered also requires the release of a probe at the perihelion point of the sailcraft. Consequently, the lightness number of the sail undergoes a positive jump at probe release, reaching a value significantly greater than one, thus allowing the sailcraft to reach a very high terminal speed at a sail-jettison distance of 5 AU. An ideal sail force model and the two-body dynamic equations are utilized in the current study. The sail cone and clock angles are the control variables. The mission requirements result in a discontinuous, time-optimal control problem, which is solved by the application of an indirect method, involving the solution to a multi-point boundary value problem. A number of mission scenarios are investigated by varying relevant parameters, such as the mass of the probe, the minimum perihelion distance and the initial sail lightness number. The paper presents data regarding flight time and terminal speeds at distances ranging from 5 to 500 AU. In some cases, the final jettison velocities are as high as 60 AU per year, indicating the possibility of a dramatic reduction in the flight time to make the 500 AU missions feasible. [View Full Paper]

AAS 13 – 222

Preliminary Development of an Optimized Lambert Problem Solver for Targets in Elliptical Orbits

David B. Spencer and **Brian S. Shank**, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.

This paper investigates the solution of Lambert's Problem for targets in elliptical orbits. Preliminary efforts are made in developing a mission design software tool to determine the optimal interplanetary trajectory and final capture orbit based on mission constraints and requirements between a departure and arrival body. Integration of the Applied Research Laboratory Trade Space Visualizer software permits a mission designer to visually inspect the multi-dimensional trade space and investigate regions of feasible trajectories. [View Full Paper]

AAS 13 – 223

L_5 MISSION DESIGN TARGETING STRATEGY

Pedro J. Llanos, Flight Mechanics Group, GMV Space and Defence, S.A., Madrid, Spain; **James K. Miller**, Navigation Consultant, Los Angeles, California, U.S.A.; **Gerald R. Hintz**, Astronautical Engineering Department, University of Southern California, Los Angeles, California, U.S.A.

A numerical method for targeting both the transfer orbit and Trojan orbit around the triangular points in the Sun-Earth system is implemented and then tested with a conic approach. This method generates end-to-end trajectories from a low Earth parking orbit at 200-km altitude and 28.5º inclination, using a high fidelity model allowing for injection velocity corrections at the parking orbit. Either the position or velocity at arrival in the Trojan orbit around L_5 may be targeted. During the injection velocity correction, we use the classical and hyperbolic elements to target the desired orientation and radius of periapsis. [View Full Paper]

AAS 13 – 224

Mars Entry Trajectory Planning for Higher Elevation Landing

Luis Soler, **Ahmad Khatib** and **Kenneth D. Mease**, Department of Mechanical and Aerospace Engineering, University of California, Irvine, California, U.S.A.

Achieving higher elevation landing sites requires parachute deployment altitude control. Bank profiles are computed that maximize a weighted combination of final altitude and control authority. Then a planning scheme is proposed that yields trajectories with near-optimal performance and yet is suitable for onboard rapid planning and re-planning. The bank profile is parameterized and the planning problem is posed and solved as a nonlinear programming problem. A comparison shows that the performance of the solutions is only slightly reduced relative to that of the optimal solutions.
[View Full Paper]

AAS 13 – 225

(Paper Withdrawn)

AAS 13 – 226

On the Nature of Earth-Mars Porkchop Plots

Ryan C. Woolley and **Charles W. Whetsel**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Porkchop plots are a quick and convenient tool to help mission designers plan ballistic trajectories between two bodies. Parameter contours give rise to the familiar "porkchop" shape. Each synodic period the pattern repeats, but not exactly, primarily due to differences in inclination and non-zero eccentricity. In this paper we examine the morphological features of Earth-to-Mars porkchop plots and the orbital characteristics that create them. These results are compared to idealistic and optimized transfers. Conclusions are drawn about "good" opportunities versus "bad" opportunities for different mission applications. [View Full Paper]

AAS 13 – 227

Derivative Analysis and Algorithm Modification of the Transverse-Eccentricity-Based Lambert's Problem

Changxuan Wen, **Yushan Zhao** and **Peng Shi**, School of Astronautics, Beihang University, Haidian District, Beijing, China

The classical Lambert's problem can be parameterized and solved through the transverse eccentricity component. A further study is conducted to calculate the derivative of the transverse-eccentricity-based Lambert's problem and to modify its algorithm. Results show that the derivative of a direct Lambert's problem is positive and continuous, which verifies that the transfer-time monotonically increases with the transverse eccentricity; however, the derivative of a multi-revolution Lambert's problem increases from negative to positive, indicating that the transfer-time decreases to the minimum firstly, and then increases to infinity. The original solution algorithm is promoted by introducing the analytic derivative. Numerical simulations for different cases show that, compared with the two existing transverse-eccentricity-based methods, the average computational time cost decreases by 65.5% and 39.8%, respectively. [View Full Paper]

AAS 13 – 228

Homotopy Method for Minimum Fuel Rendezvous Problem With Gravity Assists

Hao Huang and **Chao Han**, School of Astronautics, Beihang University, Haidian District, Beijing, China; **Qi Gong**, Department of Applied Mathematics and Statistics, University of California, Santa Cruz, California, U.S.A.

This paper considers fuel-optimal rendezvous problem with gravity-assist. Pseudo-spectral method is used to solve energy-optimal problem first, in order to provide accurate estimation of the unknowns for indirect method. Such accurate initial guess, together with a homotopy approach, improves the convergence property of indirect type of methods. The proposed approach is applied to Earth-to-Uranus trajectory optimization with gravity assist from Earth and Jupiter. [View Full Paper]

AAS 13 – 229

On-Line Entry Trajectory Planning and Combined Prediction Guidance for Lunar Return

Biao Zhao, **JiFeng Guo** and **NaiGang Cui**, Harbin Institute of Technology (HIT), Nan Gang District, Harbin, China; **Ping Wang**, China Academy of Space Technology (CAST), Beijing, China

For the lunar return mission, a concern of the entry guidance requirement is the full flight envelope applicability and landing accuracy control. The NPC method is not limited by the validity of the approximations, simplifications and empirical assumptions necessary for any analytical treatment, thus it holds greater potential to be more accurate and adaptive. However, the NPC algorithms in the literature which merely predict based on the terminal condition cannot guarantee to meet the g-load constraint. To solve this problem, we combine NPC methods with an analytical constant drag acceleration method, and propose a simple and effective integrated guidance strategy. [View Full Paper]

SESSION 4: SPECIAL SESSION: MARS SCIENCE LABORATORY (MSL) I
Chair: Kenneth Williams, KinetX, Inc.

AAS 13 – 230
(Paper Withdrawn)

AAS 13 – 232

Mars Science Laboratory Interplanetary Navigation Performance

Tomas J. Martin-Mur, **Gerhard Kruizinga** and **Mau Wong**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Mars Science Laboratory spacecraft, carrying the Curiosity rover to Mars, hit the top of the Martian atmosphere just 200 meters from where it had been predicted more than six days earlier, and 2.6 million kilometers away. This unexpected level of accuracy was achieved by a combination of factors including: spacecraft performance, tracking data processing, dynamical modeling choices, and navigation filter setup. This paper will describe our best understanding of what were the factors that contributed to this excellent interplanetary trajectory prediction performance. The accurate interplanetary navigation contributed to the very precise landing performance, and to the overall success of the mission. [View Full Paper]

AAS 13 – 234

2011 Mars Science Laboratory Trajectory Reconstruction and Performance from Launch Through Landing

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

The Mars Science Laboratory (MSL) mission successfully launched on an Atlas V 541 Expendable Evolved Launch Vehicle (EELV) from the Eastern Test Range (ETR) at Cape Canaveral Air Force Station (CCAFS) in Florida at 15:02:00 UTC on November 26th, 2011. At 15:52:06 UTC, six minutes after the MSL spacecraft separated from the Centaur upper stage, the spacecraft transmitter was turned on and in less than 20 s spacecraft carrier lock was achieved at the Universal Space Network (USN) Dongara tracking station located in Western Australia. MSL, carrying the most sophisticated rover ever sent to Mars, entered the Martian atmosphere at 05:10:46 SpaceCraft Event Time (SCET) UTC, and landed inside Gale Crater at 05:17:57 SCET UTC on August 6th, 2012. Confirmation of nominal landing was received at the Deep Space Network (DSN) Canberra tracking station via the Mars Odyssey relay spacecraft at 05:31:45 Earth Received Time (ERT) UTC. This paper summarizes in detail the actual vs. predicted trajectory performance in terms of launch vehicle events, launch vehicle injection performance, actual DSN/USN spacecraft lockup, trajectory correction maneuver performance, Entry, Descent, and Landing events, and overall trajectory and geometry characteristics. [View Full Paper]

AAS 13 – 235

The Entry Controller for the Mars Science Laboratory

Paul B. Brugarolas, **A. Miguel San Martin** and **Edward C. Wong**, Guidance and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Mars Science Laboratory (MSL) Entry Descent and Landing (EDL) system delivered a rover named Curiosity to Gale crater (Mars) on August 5th, 2012. MSL EDL used an entry Guidance Navigation and Control (GNC) system to achieve its landing target objectives. The entry guidance law guided the vehicle by modulating the lift vector through bank commands. The navigation filter integrated Descent Inertial Measurement Unit (DIMU) measurements to estimate position and attitude. The entry controller commanded the propulsive Reaction Control System (RCS) to achieve 3-axis attitude control during the exoatmospheric phase and bank angle tracking and angle-of-attack and sideslip rate damping during the atmospheric entry phase. This paper describes the design and the as-flown performance of the entry controller. [View Full Paper]

AAS 13 – 236

Mars Science Laboratory Entry, Descent, and Landing System Overview and Preliminary Flight Performance Results

Adam D. Steltzner, **A. Miguel San Martin**, **Tommaso P. Rivellini** and **Allen Chen**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Mars Science Laboratory project recently placed the Curiosity rover safely on the surface of Mars. With the success of the landing system, the performance envelope of entry, descent, and landing (EDL) capabilities has been extended over the previous state of the art. This paper will present an overview of the MSL entry, descent and landing system design and preliminary flight performance results. [View Full Paper]

AAS 13 – 237
(Paper Withdrawn)

AAS 13 – 238

The Development of the MSL Guidance, Navigation, and Control System for Entry, Descent, and Landing

A. Miguel San Martin, **Steven W. Lee** and **Edward C. Wong**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

On August 5, 2012, the Mars Science Laboratory (MSL) mission successfully delivered the Curiosity rover to its intended target in Gale Crater. It was the most complex and ambitious landing in the history of the red planet. A key component of the landing system, the requirements for which were driven by the mission ambitious science goals, was the Guidance, Navigation, and Control (GN&C) system. This paper will describe the technical challenges of the MSL GN&C system, the resulting architecture and design needed to meet those challenges, and the development process used for its implementation and testing. [View Full Paper]

AAS 13 – 419

Post-Flight EDL Entry Guidance Performance of the 2011 Mars Science Laboratory Mission

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The 2011 Mars Science Laboratory was the first Mars guided entry which safely delivered the rover to a landing within a touchdown ellipse of 19.1 km x 6.9 km. The Entry Terminal Point Controller guidance algorithm is derived from the final phase Apollo Command Module guidance and, like Apollo, modulates the bank angle to control the range flown. The guided entry performed as designed without any significant exceptions. The Curiosity rover was delivered about 2.2 km from the expected touchdown. This miss distance is attributed to little time to correct the downrange drift from the final bank reversal and a suspected tailwind during heading alignment. The successful guided entry for the Mars Science Laboratory lays the foundation for future Mars missions to improve upon. [View Full Paper]

AAS 13 – 420

Assessment of the Mars Science Laboratory Entry, Descent, and Landing Simulation

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On August 5, 2012, the Mars Science Laboratory rover, Curiosity, successfully landed inside Gale Crater. This landing was the seventh successful landing and fourth rover to be delivered to Mars. Weighing nearly one metric ton, Curiosity is the largest and most complex rover ever sent to investigate another planet. Safely landing such a large payload required an innovative Entry, Descent, and Landing system, which included the first guided entry at Mars, the largest supersonic parachute ever flown at Mars, and a novel Sky Crane landing system. A complete, end-to-end, six degree-of-freedom, multi-body computer simulation of the Mars Science Laboratory Entry, Descent, and Landing sequence was developed at the NASA Langley Research Center. In-flight data gathered during the successful landing is compared to pre-flight statistical distributions, predicted by the simulation. These comparisons provide insight into both the accuracy of the simulation and the overall performance of the vehicle.
[View Full Paper]

AAS 13 – 421

Mars Science Laboratory Entry Descent and Landing Simulation Using DSENDS

P. Daniel Burkhart, **Jordi Casoliva** and **Bob Balaram**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The most recent planetary science mission to Mars was Mars Science Laboratory (MSL) with the Curiosity rover, launched November 26, 2011 and landed at Gale Crater on August 6, 2012. This spacecraft was the first use at Mars of a complete closed-loop Guidance Navigation and Control (GN&C) system, including guided entry with a lifting body that greatly reduces dispersions during the Entry, Descent and Landing (EDL) phase to achieve a 25 *km* x 20 *km* landing error relative to the selected Gale Crater landing target. In order to confirm meeting the above landing criteria, high-fidelity simulation of the EDL phase is required. The tool used for 6DOF EDL trajectory verification analysis is Dynamics Simulator for Entry, Descent and Surface landing (DSENDS), which is a high-fidelity simulation tool from JPLs Dynamics and Real-Time Simulation Laboratory for the development, test and operations of aero-flight vehicles. DSENDS inherent capability is augmented for MSL with project-specific models of atmosphere, aerodynamics, sensors and thrusters along with GN&C flight software to enable high-fidelity trajectory simulation. This paper will present the model integration and independent verification experience of the JPL EDL trajectory analysis team.
[View Full Paper]

SESSION 5: SPACE-SURVEILLANCE TRACKING
Chair: Dr. David Spencer, Pennsylvania State University

AAS 13 – 239

Best Hypotheses Search on Iso-Energy-Grid for Initial Orbit Determination and Track Association

Jan A. Siminski, **Oliver Montenbruck**, **Hauke Fiedler** and **Martin Weigel**, Deutsches Zentrum für Luft- und Raumfahrt (DLR), German Space Operations Center (GSOC), Wessling, Germany

Debris populating the geostationary orbit is mainly observed by ground-based optical telescopes. Short measurement arcs, known as tracklets, provide line-of-sight information along with the associated rates of change. In view of their limited duration, individual tracklets cannot be used to determine a full set of orbital elements for the observed object. Multiple hypotheses filter methods have, therefore, been proposed to associate independent tracklets and to combine them for initial orbit determination. Using a traditional search grid for the admissible region, these methods become computationally intensive with an increasing number of initial hypotheses. As an alternative, this paper proposes a minimum search method to find the best matching orbit hypotheses. The effectiveness of the presented method is assessed using simulated measurements.
[View Full Paper]

AAS 13 – 240

A Catalogue-Wide Implementation of General Perturbations Orbit Determination Extrapolated From Higher Order Orbital Theory Solutions

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The proliferation of the use of higher-order orbital theories (HOTs) has greatly expanded satellite state estimate accuracy expectations, yet much of the existing space surveillance software and infrastructure has been built around the Simplified General Perturbations Theory #4 (SGP4) analytic orbital theory and its associated two-line element set (TLE). One approach to realizing greater orbital accuracy without modifying recipients' communications and processing software is the use of the "extrapolation differential correction," in which the analyst uses a HOT ephemeris (of which some portion is propagated into the future) to create synthesized sensor observations and employs these to perform a correction with the analytic theory to produce the desired TLE. By fitting a high-fidelity future prediction, the analytic theory can inherit a substantial measure of the HOT's accuracy. This methodology, previously used on only a small number of satellites, has been prepared for catalogue-wide deployment at the Joint Space Operations Center; and satellites will be transferred to this approach in groups until most of the space catalogue is maintained this way. Full-catalogue test results show a substantial improvement in state estimate accuracy, as well as an extension of the element set's useful life for many orbital regions. [View Full Paper]

AAS 13 – 241

Automated Uncorrelated Track Resolution With the Search And Determine Integrated Environment (SADIE)

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Kathy Borelli, KJS Consulting; Makawao, Hawaii, U.S.A.;
Jason Addison and **Keric Hill**, Pacific Defense Solutions; Kihei, Hawaii, U.S.A.;
Bruce Duncan and **Kevin Roe**, The Boeing Co., Kihei, Hawaii, U.S.A.

A new high performance computing software applications package called the Search and Determine Integrated Environment (SADIE) is being jointly developed and refined by the Air Force and Naval Research Laboratories (AFRL and NRL) to automatically resolve uncorrelated tracks (UCTs) and build a more complete space object catalog for improved Space Situational Awareness (SSA). The motivation for SADIE is to respond to very challenging needs identified by and guidance received from Air Force Space Command (AFSPC) and other senior leaders to develop this technology to support the evolving Joint Space Operations Center (JSpOC) and Alternate Space Control Center (ASC2)-Dahlgren. The SADIE suite includes modification and integration of legacy applications and software components that include Search And Determine (SAD), Satellite Identification (SID), and Parallel Catalog (ParCat), as well as other utilities and scripts to enable end-to-end catalog building and maintenance in a parallel processing environment. SADIE is being developed to handle large catalog building challenges in all orbit regimes and includes the automatic processing of radar, fence, and optical data. Promising real data results are provided for the processing of low Earth radar and Air Force Space Surveillance System fence observations as well as Space Surveillance Telescope optical data. [View Full Paper]

AAS 13 – 242

Gaussian Mixture PHD Filter for Space Object Tracking

Yang Cheng, Department of Aerospace Engineering, Mississippi State University, Mississippi State, Mississippi, U.S.A.; **Kyle J. DeMars**, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.; **Carolin Früh**, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.; **Moriba K. Jah**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

A Gaussian mixture Probability Hypothesis Density (PHD) filter for multiple space object tracking is presented. The PHD filter is a computationally tractable approximate Bayesian multi-object filter based on finite set statistics. The intensity of the Gaussian mixture PHD filter is represented by a variable-size Gaussian mixture, which is propagated and updated by a Gaussian mixture filter that accounts for the nonlinear effect of long-term orbit propagation. A numerical example is used to demonstrate the viability of the filter for space object tracking. [View Full Paper]

AAS 13 – 243
(Paper Withdrawn)

AAS 13 – 244
(Paper Withdrawn)

AAS 13 – 245
Association of Satellite Observations Using Bayesian Inference

Christopher Binz and **Liam Healy**, Mathematics and Orbit Dynamics Section, Naval Research Laboratory, Washington, DC, U.S.A.

When observing satellites in an increasingly cluttered space environment, ambiguity in measurement association often arises. By using principles of probabilistic, or Bayesian, inference, we can assign numerical values of probability to the different possible associations. Several methods for handling ambiguous satellite observations are discussed, including Probabilistic Data Association (PDA) and Multiple Hypothesis Tracking (MHT). We present a comparison of these methods for a small number of observations and satellites, with a simplified motion and observation models. Filtering performance is characterized for four representative scenarios, including satellite breakups and conjunctions. [View Full Paper]

AAS 13 – 246
(Paper Withdrawn)

AAS 13 – 247
(Paper Withdrawn)

AAS 13 – 248
GEO Observability From Earth-Moon Libration Point Orbits

Nathan Parrish, Jeffrey S. Parker and Ben K. Bradley, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Colorado, U.S.A.

The effectiveness and feasibility of performing Space-Based Space Surveillance (SBSS) of Earth-orbiting objects from Earth-Moon libration point orbits (LPOs) about L_1, L_2, or L_3 are examined. Visibility analyses are performed on a host of objects with a range of inclinations in Earth orbit from an L_3 LPO. It is found that the geosynchronous (GEO) belt is the most promising regime to observe from an LPO. Observability and brightness were considered for a subset of the GEO catalog, finding that the entire GEO belt is visible for days on end, but at 5 magnitudes dimmer than as seen from the ground. [View Full Paper]

SESSION 6: LOW-THRUST TRAJECTORY DESIGN
Chair: Dr. Hanspeter Schaub, University of Colorado

AAS 13 – 249

Conception of Quasi Time-Optimal Receding Horizon Control Algorithm Application to Continuous-Thrust Orbital Rendezvous

Piotr Felisiak and **Krzysztof Sibilski**, Faculty of Mechanical and Power Engineering, Wrocław University of Technology, Poland

This paper presents conception of solution for orbital rendezvous between an active chaser satellite and nonmaneuvering target object which is moving in a known circular orbit. The variable-mass chaser satellite is equipped with a continuous-thrust propulsion. The aim of the work is to find a control resulting in quasi-optimal rendezvous trajectory. This work approaches the problem using model predictive control. A proposal of solution is based on a version of Quasi Time-Optimal Receding Horizon Control (QTO-RHC) algorithm. This method is noise resistant and able to effectively handle with various constraints. In this survey an optimization performance measure is expressed by a compromise between the transfer time and integral of squared control signal (expenditure of fuel). The problem includes constraints on amount of used fuel and approach velocity to match the velocity of the docking port. The paper contains also results for simplified case. [View Full Paper]

AAS 13 – 250

Hohmann Spiral Transfer With Inclination Change Performed By Low-Thrust System

Steven Owens and **Malcolm Macdonald**, Advanced Space Concepts Laboratory, Mechanical and Aerospace Department, University of Strathclyde, Glasgow, United Kingdom

This paper investigates the Hohmann Spiral Transfer (HST), an orbit transfer method previously developed by the authors incorporating both high and low-thrust propulsion systems, using the low-thrust system to perform an inclination change as well as orbit transfer. The HST is similar to the bi-elliptic transfer as the high-thrust system is first used to propel the spacecraft beyond the target where it is used again to circularize at an intermediate orbit. The low-thrust system is then activated and, while maintaining this orbit altitude, used to change the orbit inclination to suit the mission specification. The low-thrust system is then used again to reduce the spacecraft altitude by spiraling in-toward the target orbit. An analytical analysis of the HST utilizing the low-thrust system for the inclination change is performed which allows a critical specific impulse ratio to be derived determining the point at which the HST consumes the same amount of fuel as the Hohmann transfer. A critical ratio is found for both a circular and elliptical initial orbit. These equations are validated by a numerical approach before being compared to the HST utilizing the high-thrust system to perform the inclination change. An additional critical ratio comparing the HST utilizing the low-thrust system for the inclination change with its high-thrust counterpart is derived and by using these three critical ratios together, it can be determined when each transfer offers the lowest fuel mass consumption. Initial analyses have shown the HST utilizing low-thrust inclination change to offer the greatest benefit at low $R2$ ($R2 \rightarrow R1$) and large ΔI ($\Delta I > 30^{\circ}$). A novel numerical optimization process which could be used to optimize the trajectory is also introduced. [View Full Paper]

AAS 13 – 251

Approximation of Constraint Low-Thrust Space Trajectories in Three Body Dynamic Models Using Fourier Series

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

Finite Fourier series were previously implemented successfully in approximating two-dimensional continuous-thrust trajectories in two-body dynamic models. In this paper, Finite Fourier series are implemented for low-thrust trajectory approximation, in the presence of thrust acceleration constraints, in the three body dynamic model. This approximation enables the feasibility assessment of low-thrust trajectories, especially in the presence of thrust level constraint. The resulting approximated trajectory can be used as initial guess in optimization techniques. [View Full Paper]

AAS 13 – 252
(Paper Withdrawn)

AAS 13 – 253
(Paper Withdrawn)

AAS 13 – 254
(Paper Withdrawn)

AAS 13 – 255
A Low Energy, Low Thrust Unified Solver for Rapid Mission Design

Nitin Arora, The Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.; **Nathan Strange**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Recent studies of a manned cislunar way point base at the moon are driving the need to rapidly compute low-energy, low thrust (le-lt) trajectories to Earth-Moon L1/L2 Lagrange points. Existing methods are hard to setup and suffer from large compute times. We propose LOTUS a robust, near-optimal solver, capable of rapidly computing near optimal le-lt trajectories. The algorithm takes advantage of a low thrust feedback control law (Q-Law) along with a novel, heuristic based le-lt patch point selection strategy implemented via a backward solution methodology. LOTUS is applied to a solar electric propulsion powered, Earth-Moon L2 transfer design problem. On the order of 700, near optimal le-lt transfers solutions are computed in ~ 3.5 hrs. [View Full Paper]

AAS 13 – 256
Satellite Power Subsystem Requirements for Time-Constrained Electric Orbit-Raising With Minimal Radiation Impact

Atri Dutta, **Paola Libraro**, **N. Jeremy Kasdin** and **Edgar Choueiri**, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton New Jersey, U.S.A.

In this paper, we consider the problem of orbit-raising of all-electric satellites. In order to minimize the impact of radiation during the electric orbit-raising maneuver, we formulate an optimization problem that minimizes radiation fluence along the trajectory. We use a direct optimization approach to solve the resulting optimal control problem for a variety of mission scenarios. We identify combinations of electric thrusters and starting orbits that deploy a satellite in GEO in 6 months, and identify the mass and power requirements of the solar arrays for small and large classes of telecommunication satellites. [View Full Paper]

AAS 13 – 257

Multi-Objective Optimisation of Many-Revolution, Low-Thrust Orbit Raising for Destiny Mission

Federico Zuiani and **Yasuhiro Kawakatsu**, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara-shi, Kanagawa-ken, Japan; **Massimiliano Vasile**, Mechanical and Aerospace Department, University of Strathclyde, Glasgow, United Kingdom

This work will present a Multi-Objective approach to the design of the initial, Low-Thrust orbit raising phase for JAXA's proposed technology demonstrator mission DESTINY. The proposed approach includes a simplified model for Low Thrust, many-revolution transfers, based on an analytical orbital averaging technique, and a simplified control parameterisation. Eclipses and J_2 perturbation are also accounted for. This is combined with a stochastic optimisation algorithm to solve optimisation problems in which conflicting performance figures of DESTINY's trajectory design are concurrently optimised. It will be shown that the proposed approach provides for a good preliminary investigation of the launch window and helps identifying critical issues to be addressed in future design phases. [View Full Paper]

AAS 13 – 258

Robust Optimal Control of Low-Thrust Interplanetary Transfers

P. Di Lizia, **R. Armellin** and **F. Bernelli-Zazzera**, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Milano, Italy

Continuous-thrust orbit transfers are designed by solving an optimal control problem that minimizes fuel consumption while satisfying mission constraints. The optimal control problem is usually solved in nominal conditions: at the design stage, the dynamics modeling is supposed to exactly represent the reality. An algorithm to include uncertain parameters and boundary conditions is presented. This is based on the high-order expansion of the solution of the two-point boundary value problem associated to the optimal control problem with respect to uncertainties. Illustrative applications are presented in the frame of the optimal low-thrust transfer to asteroid 1996 FG_3.
[View Full Paper]

AAS 13 – 472

Low-Thrust Egalitarian Peer-to-Peer Maneuvers for Servicing Satellites in Circular Constellations

Atri Dutta, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton New Jersey, U.S.A.

Peer-to-Peer maneuvers are integral components of distributed strategies to deliver fuel, upgraded avionics and other commodities to a system of multiple satellites. In this paper, we consider the problem of minimum-time low-thrust Egalitarian Peer-to-Peer servicing, in which the active satellites are allowed to interchange their orbital positions at the end of the mutual exchange of commodities. We develop a methodology to determine the minimum time maneuvers required for distributed servicing and demonstrate that a distributed strategy yields a significantly smaller mission time compared to a centralized single service vehicle strategy. [View Full Paper]

AAS 13 – 473

Minimum-Fuel Low-Thrust Rendezvous Trajectories Via Swarming Algorithm

Mauro Pontani, University of Rome "La Sapienza", Rome, Italy; **Bruce A. Conway**, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.

The particle swarm optimization technique is a population-based heuristic method developed in recent years and successfully applied in several fields of research. It 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, minimum-fuel rendezvous trajectories in a rotating Euler-Hill frame. Hamiltonian methods are employed to translate the related optimal control problem into a parameter optimization problem, in which the parameter set is composed of the initial values of the adjoint variables. A switching function is also defined, and determines the optimal sequence and durations of thrust and coast arcs. The algorithm at hand is extremely easy to program. Nevertheless, it proves to be effective, reliable, and numerically accurate in solving several qualitatively different test cases.
[View Full Paper]

SESSION 7: ORBITAL DYNAMICS NEAR SMALL-BODY
Chair: Dr. Steve Broschart, Jet Propulsion Laboratory

AAS 13 – 259
Comet Thermal Model for Navigation

Pedro J. Llanos, Flight Mechanics Group, GMV Space and Defence, S.A., Madrid, Spain; **James K. Miller**, Navigation Consultant, Los Angeles, California, U.S.A.; **Gerald R. Hintz**, Astronautical Engineering Department, University of Southern California, Los Angeles, California, U.S.A.

We implement a numerical model to analyze the thermodynamics that can be used for navigation and orbit determination of future space missions to small bodies. Unlike past models that use a spherical homogeneous model, our model includes the real non-spherical shape of asteroid 433 Eros. The surface temperature map is expressed as a function of latitude and longitude directions for different initial isothermal temperatures. The lack of spherical symmetry is modeled along with the long and short term temperature variations as a consequence of the orbital and spin axis rotations of the body. [View Full Paper]

AAS 13 – 260
(Paper Withdrawn)

AAS 13 – 261
Multiple Sliding Surface Guidance Applied at Binary Asteroid Systems

Julie Bellerose, Research Faculty, Carnegie Mellon University Silicon Valley, and NASA Amers Research Center, Moffett Field, California, U.S.A.; **Roberto Furfaro**, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.; **Dario Cersosimo**, Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, Missouri, U.S.A.

Proximity operations at binary asteroid systems involve higher degrees of complexity due to added perturbations. In this paper, we adapt a Multiple Sliding Surface Guidance (MSSG) algorithm developed for close proximity operations at a single asteroid, and extend its applicability to binary asteroid systems. The advantage of using MSSG is that no trajectory is needed to be computed offline as the commands use the spacecraft accelerations directly. We show simulations of a two-sphere binary systems. The velocity cost and associated transfer times show to be minimal. [View Full Paper]

AAS 13 – 262

ZEM/ZEV Guidance Approach for Asteroid Touch-And-Go Sample Collection Maneuvers

Brian Gaudet, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.; **Roberto Furfaro**, Department of Systems and Industrial Engineering, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona, U.S.A.

Future asteroid sample return missions (e.g. NASA OSIRIS REx mission to 1999 RQ_{36}) will require the spacecraft to touch down to the asteroid's surface to collect samples for short time periods (~ 5 sec). Such maneuvers are called Touch-And-Go (TAG) and are critical for effective sampling. Importantly, the final TAG descent to the selected asteroid's surface must be unpowered in order to avoid sample contamination. This paper presents a ZEM/ZEV-based guidance approach with selected waypoints to autonomously reach a point 30m above the desired landing site. The constraints imposed by the navigation system result in a small velocity error at the initiation of the coasting phase, which results in unacceptable landing accuracy. We show that such residual velocity can be reduced to an acceptable level provided the spacecraft is allowed to hover prior to the coasting descent phase. A set of Monte Carlo simulations is executed to validate the guidance approach. These simulations model a novel state estimation algorithm that enables real-time estimation of the spacecraft's state in the asteroid body-centered reference frame, as well as a mapping of the guidance law's commanded thrust to the pulsed thrusters. The simulations demonstrate an unprecedented level of accuracy for the TAG maneuver. [View Full Paper]

AAS 13 – 263

(Paper Withdrawn)

AAS 13 – 264

Estimation of Asteroid Model Parameters Using Particle Filters

Brian Gaudet, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.; **Roberto Furfaro**, Department of Systems and Industrial Engineering, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona, U.S.A.

Planning of open-loop maneuvers in an asteroid's dynamic environment requires the ability to estimate the forces acting on the spacecraft as a function of position and time. These forces can be estimated using a mathematical model of the asteroid provided that the model parameters may be accurately inferred. In this paper we demonstrate how a particle filter can quickly and accurately estimate these model parameters using the spacecraft's average commanded thrust whilst hovering at two locations in close proximity to the asteroid. The accuracy of the particle filter is then compared to that of two state of the art optimization algorithms. We also show how this method can easily be extended to estimate internal gradients in the asteroid's density.
[View Full Paper]

AAS 13 – 265

Generalized Density Distribution Estimation for Small Bodies

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

Scientific interest in small solar system bodies has been growing significantly during the last decade, with a number of mission studies, actual missions, and planned future missions in the works. In order to support the close proximity operations of the mission it is necessary to develop an accurate gravity field valid to the surface. One way to construct an accurate gravity field model is to assume that the body density is homogeneous and compute the potential/acceleration of the spacecraft by shape model integration. However, for a majority of asteroid, this homogeneous density assumption may not be suitable, and the measured gravity field from orbit determination process often differs from that generated by shape model integration. In this paper, we investigate the discrepancies between the measured gravity field and the gravity field generated by homogeneous density assumption. Using this difference, we can constrain the internal density distribution of an asteroid, which motivates a generalized density estimation approach to recover a representation of the true density distribution of the body.
[View Full Paper]

AAS 13 – 335

Characteristics of Quasi-Terminator Orbits Near Primitive Bodies

Stephen B. Broschart, **Gregory Lantoine** and **Daniel J. Grebow**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Quasi-terminator orbits are introduced as a class of quasi-periodic trajectories in the solar radiation pressure (SRP) perturbed Hill dynamics. These orbits offer significant displacements along the Sun-direction without the need for station-keeping maneuvers. Thus, quasi-terminator orbits have application to primitive-body mapping missions, where a variety of observation geometries relative to the Sun (or other directions) can be achieved. This paper describes the characteristics of these orbits as a function of normalized SRP strength and invariant torus frequency ratio and presents a discussion of mission design considerations for a global surface mapping orbit design.
[View Full Paper]

AAS 13 – 484

Passive Sorting of Asteroid Material Using Solar Radiation Pressure

D. García Yárnoz, **J. P. Sánchez Cuartielles** and **C. R. McInnes**, Advanced Space Concepts Laboratory, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, United Kingdom

Understanding dust dynamics in asteroid environments is key for future science missions to asteroids and, in the long-term, also for asteroid exploitation. This paper proposes a novel way of manipulating asteroid material by means of solar radiation pressure (SRP). We envisage a method for passively sorting material as a function of its grain size where SRP is used as a passive in-situ 'mass spectrometer'. The analysis shows that this novel method allows an effective sorting of regolith material. This has immediate applications for sample return, and in-situ resource utilisation to separate different regolith particle sizes. [View Full Paper]

AAS 13 – 492

Automated Design of Propellant-Optimal, End-to-End, Low-Thrust Trajectories for Trojan Asteroid Tours

Jeffrey Stuart and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Roby Wilson**, Inner Planet Missions Analysis Group, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Sun-Jupiter Trojan asteroids are celestial bodies of great scientific interest as well as potential resources offering mineral resources for long-term human exploration of the solar system. Previous investigations under this project have addressed the automated design of tours within the asteroid swarm. The current automation scheme is now expanded by incorporating options for a complete trajectory design approach from Earth departure through a tour of the Trojan asteroids. Computational aspects of the design procedure are automated such that end-to-end trajectories are generated with a minimum of human interaction after key elements associated with a proposed mission concept are specified. [View Full Paper]

AAS 13 – 495
(Paper Withdrawn)

AAS 13 – 496
(Paper Withdrawn)

AAS 13 – 497

A Trajectory Optimization Strategy for a Multiple Rendezvous Mission With Trojan Asteroids

Lucas Brémond and **Ryu Funase**, Department of Aeronautics and Astronautics, Graduate School of Engineering, The University of Tokyo, Japan;
Yuichi Tsuda and **Jun'ichiro Kawaguchi**, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

In the overall context of a solar sail mission in the vicinity of the Trojan asteroids swarm around the L4 Lagrange point, the purpose of this work is to find an optimal sequence of asteroids rendezvous that accommodates given mission constraints. A currently considered strategy to solve this problem will be presented and design choices will be outlined. A subset of the Trojan asteroids database is first extracted based on orbital elements considerations and a tree containing all the potential sequences is generated. A first set of pruning techniques is applied to the tree in order to quickly reduce the search space by several orders of magnitude. A global optimization method is then used: it combines a branch-and-bound approach and an evolutionary algorithm to find good sequence order, departure date, transfer and coasting durations. In order to enable a fast computation of potential transfer costs, the dynamics are linearized around L4 and the ΔVs are computed analytically. Preliminary results show a drastic reduction of the search space along with a reasonable accuracy on the cost prediction. This method has been used to analyze a tour scenario starting from 588 Achilles and including three rendezvous; the final result provides a list of sequences of potential interest.
[View Full Paper]

SESSION 8: SPECIAL SESSION
GRAVITY RECOVERY AND INTERIOR LABORATORY (GRAIL)
Chair: Tomas Martin-Mur, Jet Propulsion Laboratory

AAS 13 – 266
(Paper Withdrawn)

AAS 13 – 267
(Paper Withdrawn)

AAS 13 – 268
Execution-Error Modeling and Analysis of the GRAIL Spacecraft Pair

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The GRAIL spacecraft, Ebb and Flow (aka GRAIL-A and GRAIL-B), completed their prime mission in June and extended mission in December 2012. The excellent performance of the propulsion and attitude control subsystems contributed significantly to the mission's success. In order to better understand this performance, the Navigation Team has analyzed and refined the execution-error models for ΔV maneuvers. There were enough maneuvers in the prime mission to form the basis of a model update that was used in the extended mission. This paper documents the evolution of the execution-error models along with the analysis and software used. [View Full Paper]

AAS 13 – 269
GRAIL Orbit Determination for the Science Phase and Extended Mission

Mark Ryne, **Peter Antreasian**, **Stephen Broschart**, **Kevin Criddle**, **Eric Gustafson**, **David Jefferson**, **Eunice Lau**, **Hui Ying Wen** and **Tung-Han You**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Gravity Recovery and Interior Laboratory Mission (GRAIL) is the 11th mission of the NASA Discovery Program. Its objective is to help answer fundamental questions about the Moon's internal structure, thermal evolution, and collisional history. GRAIL employs twin spacecraft, which fly in formation in low altitude polar orbits around the Moon. An improved global lunar gravity field is derived from high-precision range-rate measurements of the distance between the two spacecraft. The purpose of this paper is to describe the strategies used by the GRAIL Orbit Determination Team to overcome challenges posed during on-orbit operations. [View Full Paper]

AAS 13 – 270

The Role of GRAIL Orbit Determination in Preprocessing of Gravity Science Measurements

Gerhard Kruizinga, **Sami Asmar**, **Eugene Fahnestock**, **Nate Harvey**, **Daniel Kahan**, **Alex Konopliv**, **Kamal Oudrhiri**, **Meegyeong Paik**, **Ryan Park**, **Dmitry Strekalov**, **Michael Watkins** and **Dah-Ning Yuan**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Gravity Recovery And Interior Laboratory (GRAIL) mission has constructed a lunar gravity field with unprecedented uniform accuracy on the farside and nearside of the Moon. GRAIL lunar gravity field determination begins with preprocessing of the gravity science measurements by applying corrections for time tag error, general relativity, measurement noise and biases. Determining these corrections requires the generation of spacecraft ephemerides of an accuracy not attainable with the pre-GRAIL lunar gravity fields. Therefore, a bootstrapping strategy was developed, iterating between science data preprocessing and lunar gravity field estimation in order to construct sufficiently accurate orbit ephemerides. This paper describes the GRAIL measurements, their dependence on the spacecraft ephemerides and the role of orbit determination in the bootstrapping strategy. Simulation results will be presented that validate the bootstrapping strategy followed by bootstrapping results for flight data, which have led to the latest GRAIL lunar gravity fields. [View Full Paper]

AAS 13 – 271

GRAIL Science Data System Orbit Determination: Approach, Strategy, and Performance

Eugene Fahnestock, **Sami Asmar**, **Daniel Kahan**, **Alex Konopliv**, **Gerhard Kruizinga**, **Kamal Oudrhiri**, **Meegyeong Paik**, **Ryan Park**, **Dmitry Strekalov** and **Dah-Ning Yuan**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

This paper details orbit determination techniques and strategies employed within each stage of the larger iterative process (ref. Kruizinga et al., this meeting) of preprocessing raw GRAIL data into the gravity science measurements used within gravity field solutions. Each orbit determination pass used different data, corrections to them, and/or estimation parameters. We compare performance metrics among these passes. For example, for the primary mission, the magnitude of residuals using our orbits progressed from ≈19.4 to ≈0.077 μm/s range rate data and from ≈0.4 to ≈0.1 mm/s for Doppler data. [View Full Paper]

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High-Resolution Lunar Gravity from the Gravity Recovery And Interior Laboratory Mission

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This paper discusses an initial gravity science results from the Gravity Recovery And Interior Laboratory (GRAIL) mission. The inter-satellite and ground-based Doppler measurements during the three-month prime science phase were processed and a 420th degree and order spherical harmonics lunar gravity field, called GL0420A, was computed. The root-mean-square of measurement residuals were 0.1 mm/s for the ground-based Doppler data (10-s count time) and 0.05 micron/s for the inter-satellite data (5-s count time), respectively. The ground-based Doppler data was fitted to the expected noise level whereas the inter-satellite data has not reached the expected noise floor of 0.03 microns/s, indicating that there exists higher order gravity signal (n>420). Overall, the result shows that the lunar gravity field has improved by 3-5 orders of magnitude over knowledge from pre-GRAIL gravity field. [View Full Paper]

AAS 13 – 273

Modeling and Precise Orbit Determination in Support of Gravity Model Development for the GRAIL Mission

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J. B. Nicholas, Emergent Space Technologies, Greenbelt, Maryland, U.S.A.;
E. Mazarico, **D. E. Smith** and **M. T. Zuber**; Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.; **B. D. Loomis**, **D. S. Chinn** and **D. Caprette**, Singer Ghaffarian Technologies, Greenbelt, Maryland, U.S.A.

New and improved models of the lunar gravity field to 420x420 in spherical harmonics have been derived from the analysis of the Gravity Recovery And Interior Laboratory (GRAIL) intersatellite Ka-band tracking data. We discuss the measurement and force modeling applied to the analysis of the GRAIL data from the primary mission (March 1 to May 29, 2012), and the strategies chosen to develop the high degree solutions. We summarize the quality of the gravity models developed and their impact on GRAIL precision orbit determination. [View Full Paper]

AAS 13 – 274

Improved Precision Orbit Determination of Lunar Orbiters from the GRAIL-Derived Lunar Gravity Models

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Joseph B. Nicholas, Emergent Space Technologies, Greenbelt, Maryland, U.S.A.
Mark H. Torrence, Singer Ghaffarian Technologies, Greenbelt, Maryland, U.S.A.

High-resolution global gravity field models of the Moon were obtained from precise Ka-band range-rate measurements between the twin Gravity Recovery And Interior Laboratory (GRAIL) spacecraft. We assess the geodetic improvements in tracking data fit and orbit reconstruction quality for independent lunar orbiters, with the latest degree and order 660 spherical harmonics gravity field model developed at NASA GSFC from the primary mission data. We focus on the Lunar Reconnaissance Orbiter (LRO), but also discuss results for Lunar Prospector and the Japanese SELENE mission. In the case of LRO, in addition to radiometric tracking, we use altimetric data from the Lunar Orbiter Laser Altimeter (LOLA) to provide independent estimates of the position reconstruction accuracy. [View Full Paper]

AAS 13 – 275
(Paper Withdrawn)

SESSION 9: ORBIT DETERMINATION AND ESTIMATION THEORY II
Chair: Dr. Stefano Casotto, Università degli Studi di Padova

AAS 13 – 231

Mars Science Laboratory Orbit Determination Data Pre-Processing

Eric D. Gustafson, **Gerhard L. Kruizinga** and **Tomas J. Martin-Mur**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Mars Science Laboratory (MSL) was spin-stabilized during its cruise to Mars. We discuss the effects of spin on the radiometric data and how the orbit determination team dealt with them. Additionally, we will discuss the unplanned benefits of detailed spin modeling including attitude estimation and spacecraft clock correlation.
[View Full Paper]

AAS 13 – 233

Filter Strategies for Mars Science Laboratory Orbit Determination

Paul F. Thompson, **Eric D. Gustafson**, **Gerhard L. Kruizinga** and **Tomas J. Martin-Mur**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Mars Science Laboratory (MSL) spacecraft had ambitious navigation delivery and knowledge accuracy requirements for landing inside Gale Crater. Confidence in the orbit determination (OD) solutions was increased by investigating numerous filter strategies for solving the orbit determination problem. We will discuss the strategy for the different types of variations: for example, data types, data weights, solar pressure model covariance, and estimating versus considering model parameters. This process generated a set of plausible OD solutions that were compared to the baseline OD strategy. Even implausible or unrealistic results were helpful in isolating sensitivities in the OD solutions to certain model parameterizations or data types. [View Full Paper]

AAS 13 – 276

Measurement Uncertainty in Satellite Direction Finding With an Interferometer

Liam Healy and **Christopher Binz**, Mathematics and Orbit Dynamics Section, Naval Research Laboratory, Washington, D.C., U.S.A.

Uncertainties in a direction-finding sensor affect the determined orbit. In a radio-frequency interferometer, modeling only phase difference (timing) uncertainty with a normal distribution, the posterior probability density function of the direction is multimodal. We show that by treating the probability density function of the direction cosine as a discrete set of disconnected regions, or segments, corresponding to each mode, and computing within each mode a conventional mean and standard deviation, we can retain information that would be lost given a conventional treatment which is optimized for a unimodal result. With a corresponding generalization in other parts of the calculation, such as observation association and orbit determination, we may obtain not only improvement of results from a conventional antenna array, but the possibility that a less expensive, simplified array, that can still contribute valuable orbital knowledge, and, due to its lower cost, could enjoy more widespread deployment. We introduce and explain the notion of *Multiple Mode Combinatorial Hypothesis Least Squares* (MMCHLS), graphing the results obtained from synthesized observations, comparing with the known correct result, as an idea of how that generalization might proceed.
[View Full Paper]

AAS 13 – 277

Range-Only Initial Orbit Determination

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

Range-only initial orbit determination (IOD) is designed to derive six-dimensional orbit estimates from range measurements, their time-tags, and sensor locations. Accurate range-rate interpolants are derived from range measurements with a new interpolation algorithm that couples Lagrange and Chebyshev interpolators. The IOD measurement set thus consists of range measurements and range-rate interpolants. Reduction from the six dimensional orbit problem to a three dimensional problem is enabled with the use of Lagrange's f and g expressions as developed by Herrick in closed form. A new three-dimensional search algorithm calculates multiple six-dimensional orbit estimates using two-body dynamics. The number of solutions was found to be inversely proportional to the size of range measurement component thermal noise Sigma σ_W. Each two-body orbit estimate is used to seed an iterative nonlinear least squares orbit determination with full force model. Iterative convergence defines success for the range-only IOD estimate used. [View Full Paper]

AAS 13 – 278

Navigation of NASA's Van Allen Probes Mission

Gene A. Heyler, **Fazle E. Siddique** and **Dipak K. Srinivasan**, Space Department, The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

The Van Allen Probes Mission, part of NASA's Living With a Star Program, successfully launched on August 30th, 2012 from the Cape Canaveral Atlas-V Space Launch Complex 41. The two-year mission was designed, built, and operated by the Johns Hopkins University Applied Physics Laboratory. It consists of two spin-stabilized spacecraft, in nearly identical highly-eccentric Earth orbits, which contain instruments to study ions, electrons, and the local magnetic and electric fields of Earth's inner and outer radiation belts. The two spacecraft were launched on a single Atlas V 401 launch vehicle, and placed in orbits that cause one spacecraft to lap the other approximately four times per year. This paper describes the ground assets, navigation data, Orbit Determination (OD) software of the navigation process, the prelaunch analysis that characterized expected OD performance, and results of actual early OD performance. Details are also provided on spacecraft initial acquisition contingencies given combinations of off-line ground stations and their effect on the launch go / no-go criteria.
[View Full Paper]

AAS 13 – 279

Atmospheric Density Reconstruction Using Satellite Orbit Tomography

Michael A. Shoemaker, **Brendt Wohlberg** and **Josef Koller**, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

Improved thermospheric neutral density models are required to better predict LEO satellite orbits. This research describes a new method to estimate the density using a tomography-based approach, where the orbit states of satellites serve as the measurements. The variational equation for the semimajor axis due to perturbing drag acceleration is used to relate the change in osculating specific mechanical energy of the orbit to the integrated density over the orbit. Using several such measurements from a number of satellites, one can estimate the density scale factor (i.e. a correction to an assumed density model). The problem considered here uses measurements from 100 satellites and solves for the spatially resolved global density scale factor discretized over 324 grid elements spanning 300 to 500 km altitude. This ill-posed problem is solved using Tikhonov regularization, with the 3D gradient chosen as the regularization operator, resulting in a penalty on the spatial smoothness of the estimated density. Preliminary simulation results show that the true time-averaged density can be reconstructed to within approximately 10%, using only simulated ground-based tracking measurements separated over 5 orbital revolutions. [View Full Paper]

AAS 13 – 280

Orbit Prediction Accuracy Using Vasicek, Gaussmarkov, and Random Walk Stochastic Models

Thomas M. Johnson, Vice President, Engineering, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

Accurate predicted orbits are a significant concern for space situational awareness and catalog maintenance. A key element of this is estimation of the ballistic coefficient when its behavior is dynamic or unknown. This paper analyzes the use of the Vasicek, Gauss-Markov, and random walk stochastic models to solve for the ballistic coefficient during orbit determination. Different ballistic coefficient profiles are simulated and the effect on the definitive and predicted orbit accuracy is compared to truth under ideal tracking conditions and a typical catalog maintenance tracking schedule. Guidelines for applying these models to operational orbit determination problems are then proposed.
[View Full Paper]

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(Paper Withdrawn)

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(Paper Withdrawn)

AAS 13 – 283

Applications of Unscented and Quadrature Consider Filters Using a Modified Joseph Formulation

Kyle J. DeMars, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.;
Renato Zanetti, Vehicle Dynamics and Control, The Charles Stark Draper Laboratory, Houston, Texas, U.S.A.

Consider filters provide an approach for accounting for the effects of uncertain parameters within the measurement function when performing state updates. The consider parameters are the set of parameters which yield statistically important effects in updating the state of a system, but for which improved estimates are not required, e.g. a sensor bias. This paper develops a general covariance update equation via a Joseph formulation that is valid when considering nonlinear measurements and studies the properties of the developed method. Simulation studies for both linear and nonlinear measurements are considered and compared for both unscented and quadrature formulations of the filtering step. [View Full Paper]

AAS 13 – 284

Drag Coefficient Modeling for GRACE Using Direct Simulation Monte Carlo

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

The drag coefficient of a satellite in low Earth orbit is dependent on the gas-surface interactions, attitude, satellite geometry, spacecraft relative velocity, atmospheric composition, atmospheric temperature, and spacecraft surface properties. The Direct Simulation Monte Carlo code, DS3V, is used to develop a drag coefficient model for GRACE. The code is validated with the analytical solution for the drag coefficient of a flat plate, sphere, and cylinder and drag coefficients derived for GRACE using a flat plate model. The energy-accommodation model assumes diffuse gas-surface interactions. [View Full Paper]

AAS 13 – 286
(Paper Withdrawn)

SESSION 10: ATTITUDE DETERMINATION, DYNAMICS, AND CONTROL II
Chair: Dr. Robert G. Melton, Pennsylvania State University

AAS 13 – 287

A Generic Optimal Control Tracking Solution for Various Attitude Error Parametrizations

Ahmad Bani Younes, **James D. Turner** and **John L. Junkins**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

A generic optimal tracking control is developed where the optimal control is calculated by optimizing a universal quadratic penalty function. Several attitude error representations are presented for describing the tracking orientation error kinematics. Compact forms of attitude error equation are derived for each case. The attitude error is initially defined as the quaternion (rotation) error between the current and the reference orientation. Transformation equations are presented that enable the development of nonlinear kinematic models that are valid for arbitrarily large relative rotations and rotation rates. The nonlinear error for the equation of motion is retained, yielding a tensor-based series solution for the Co-State as a function of error dynamics. By utilizing several attitude error kinematics to describe the spacecraft rotation error, we introduce a universal quadratic penalty function of tracking errors that is consistent in each of the coordinate choices—i.e. a quadratic penalty on the MRPs error is clearly not “the same” physically as a quadratic penalty on the classical Rodrigues parameters. We utilize this universal attitude error measure expressed through approximate transformations as a positive function of each of the coordinate choices. This allows for a universal solution to many spacecraft optimal control problems and removes the dependency on the attitude coordinate choice. [View Full Paper]

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(Paper Withdrawn)

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(Paper Withdrawn)

AAS 13 – 290

Free-Molecular Flow Induced Attitude Changes of Spinning Satellites in Elliptical Orbits

Jozef C. van der Ha, Consultant, Deming, Washington, U.S.A.

This paper presents a method for obtaining the attitude changes experienced by a spinning satellite under torques induced by free-molecular flow. The results are relevant for objects in elliptical Earth orbits with perigees below about 600 km. In particular, this includes satellites and rocket bodies in geostationary transfer orbits. First, a few fundamental aspects of free-molecular flow interactions with satellite surfaces are presented, e.g. the momentum exchanges originating from Maxwell-Boltzmann's kinetic gas theory. Expressions for the forces and torques acting on typical spinning satellite configurations are given. The average change in the attitude pointing over a spin revolution is established by integrating the torque vector over the perigee region. The integral is evaluated in the form of an asymptotic series expansion. Its leading term is an analytical expression in terms of the orbital elements, the angle between velocity vector and spin-axis, the air density and scale height values, the satellite's geometrical parameters, and the coefficients modeling the molecular flow and satellite surface interactions.
[View Full Paper]

AAS 13 – 291

Using TableSat IC for the Analysis of Attitude Control and Flexible Boom Dynamics for NASA Magnetospheric Multiscale (MMS) Mission Spacecraft

Joshua A. Chabot, **Joseph J. Kelley**, **Michael A. Johnson** and **May-Win L. Thein**, Department of Mechanical Engineering, University of New Hampshire, Durham, New Hampshire, U.S.A.

The NASA Magnetospheric MultiScale (MMS) mission (to be launched in 2014) consists of four spin-stabilized spacecraft flying in precise formation. The MMS spacecraft, which have wire booms up to 60 m long, are analyzed using the UNH MMS TableSat IC, a limited 3-DOF rotation (full spin, limited nutation) table top prototype of the MMS spacecraft. A PID controller is implemented on TableSat IC to observe the effects of spin rate and nutation control on the experimental satellite bus and scaled booms. Nutation and spin are implemented independently and the behavior of the test bed with and without SDP booms is examined. The SDP booms are shown to increase the response time of the controlled platform. [View Full Paper]

AAS 13 – 292

Three-Axis Attitude Control Using Redundant Reaction Wheels With Continuous Momentum Dumping

Erik A. Hogan, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, U.S.A.; **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

A description of an attitude control system for a 3-axis stabilized spacecraft is presented. Using modified Rodrigues parameters, a globally stabilizing nonlinear feedback control law is derived that enables tracking of an arbitrary, time-varying reference attitude. This new control incorporates integral feedback while avoiding any quadratic rate feedback components. A redundant cluster of four reaction wheels is used to control the spacecraft attitude, and three magnetic torque rods are used for purposes of continuous autonomous momentum dumping. The momentum dumping strategy can employ general torque rod orientations, and is developed to take advantage of a redundant set of reaction wheels. [View Full Paper]

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(Paper Withdrawn)

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(Paper Withdrawn)

AAS 13 – 295

Chattering Attenuation Sliding Mode Control of a Satellite's Attitude

Hamidreza Nemati and **Shinji Hokamoto**, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka, Japan

This paper develops a new robust nonlinear control algorithm based on the theory of sliding mode to control the attitude of a satellite. The system comprises a satellite with three pairs of thrusters on the satellite's principal axes. Since conventional sliding mode controllers include a discontinuous function, a significant problem called chattering can occur. The main purpose of this paper is to design a new switching function in order to alleviate this drawback. Moreover, for increasing the robustness of the proposed controller, a new slope-varying hyperbolic function is utilized. Simulation results highlight the effectiveness of the proposed method. [View Full Paper]

SESSION 11: TRAJECTORY OPTIMIZATION II
Chair: Dr. T. S. Kelso, Center for Space Standards and Innovation

AAS 13 – 296

Simplified Estimation of Trajectory Influence in Preliminary Staging Studies

Eric Bourgeois, Safety Performance & Control Department, CNES - Launcher Directorate, Paris, France

Staging is a fundamental step for any launcher pre-design process. The total increment of speed to deliver is a key factor of these studies; it depends mainly on the characteristics of the orbit to reach, and also on losses induced by gravity and atmosphere. The estimation of these losses generally requires to perform a trajectory optimization, which convergence is not always guaranteed; the goal of this paper is to present a quick and robust methodology allowing to estimate losses, with a reasonable accuracy. Description, design and test of this methodology are presented. [View Full Paper]

AAS 13 – 297

Orbit Clustering Based on Transfer Cost

Eric D. Gustafson, **Juan J. Arrieta-Camacho** and **Anastassios E. Petropoulos**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

We propose using cluster analysis to perform quick screening for combinatorial global optimization problems. The key missing component currently preventing cluster analysis from use in this context is the lack of a useable metric function that defines the cost to transfer between two orbits. We study several proposed metrics and clustering algorithms, including *k*-means and the expectation maximization algorithm. We also show that proven heuristic methods such as the Q-law can be modified to work with cluster analysis. [View Full Paper]

AAS 13 – 298

Developing a Tool for the Trajectory Planning of CubeSat Missions

Alexander Ghosh and **Victoria Coverstone**, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.

Developing a modern low thrust trajectory planning tool for applications to picosatellites poses a number of unique challenges. This work discusses the development of a propellant-minimum trajectory planning tool, that combines a higher order integrator, algebraic differentiation techniques, adaptive step size control, a non-linear programming problem solver, and analysis of cumulative density functions of the control profile to generate a robust, extendable solution framework. Discussions of the lessons learned in merging these techniques, as well as a few demonstrated case studies will be included. The work will be shown to be extendable in the future towards cooperative formation flying. [View Full Paper]

AAS 13 – 299

Automatic Algorithm for Accurate Numerical Gradient Calculation in General and Complex Spacecraft Trajectories

Ricardo L. Restrepo and **Cesar A. Ocampo**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, W. R. Woolrich Laboratories, Austin, Texas, U.S.A.

An automatic algorithm for accurate numerical gradient calculations has been developed. The algorithm is based on finite differences. The novelty of the method is an automated tuning of the step size perturbation required for the method. This automation guaranties the best possible solution using these approaches without the requirement of user inputs. The algorithm treats the functions as a black box, which makes it extremely useful when general and complex problems are considered. This is the case of spacecraft trajectory design problems and complex optimization systems. An efficient procedure for the automatic implementation is presented. Examples based on Earth-Moon missions are shown to validate and demonstrate the accuracy of the method. A state transition matrix (STM) procedure has been developed as a reference for the validation of the method. [View Full Paper]

AAS 13 – 300

Source: A Matlab-Oriented Tool for Interplanetary Trajectory Global Optimization. Fundamentals

Arnaud Boutonnet, **Waldemar Martens** and **Johannes Schoenmaekers**, Mission Analysis Section, ESA-ESOC, Darmstadt, Germany

This is the first part of the presentation of SOURCE, a new Matlab-based interplanetary global optimization tool with very short execution times. The fundamentals of the algorithm are presented: first, the matrix generation, which is based on the evaluation and storage of porkchops representing the solution of Lambert problems is discussed. Special attention is given to singularities (resonant transfers) and limitations (transfer with not enough transfer time, Δv gravity assist). Then a series of filters based on matrix manipulations are presented. Finally, the last step based on dynamic programming is detailed. [View Full Paper]

AAS 13 – 301

Source: A Matlab-Oriented Tool for Interplanetary Trajectory Global Optimization. Applications

Waldemar Martens, **Arnaud Boutonnet** and **Johannes Schoenmaekers**, Mission Analysis Section, ESA-ESOC, Darmstadt, Germany

This is the second part of the presentation of SOURCE, a new Matlab-oriented interplanetary global optimization tool with very short execution times. In the first half of the paper a quasi-local optimization stage (also part of the tool), based on the same branch and pruning algorithm as the global optimization stage is discussed. In the second half the results of an application of the tool to two ESA missions are presented: JUICE and Solar Orbiter. The objective here is to validate whether the new tool can reproduce known trajectories for these missions and possibly find new options.
[View Full Paper]

AAS 13 – 302

(Paper Withdrawn)

AAS 13 – 303

Extremal Control and Guidance Solutions for Orbital Transfer With Intermediate Thrust

Dilmurat M. Azimov, Department of Mechanical Engineering, University of Hawaii at Manoa, Honolulu, Hawaii, U.S.A.

The variational problem of an extremal transfer of a spacecraft between elliptical orbits via one or more intermediate-thrust arcs with constant specific impulse in a central Newtonian field and spacecraft guidance during the transfer are considered. New analytical solutions for the transfers between two coplanar elliptical orbits via one and two intermediate-thrust arcs are obtained. It is shown that an extremal transfer with three thrust arcs would not be as fuel-efficient compared to the transfers with one and two thrust arcs. Illustrative numerical examples of extremal transfers using one and two thrust arcs are considered. It is demonstrated that an optimal two-impulsive transfer is economically advantageous compared to the cases of transfers with these thrust arcs, and the Hohmann transfers assuming that the terminal orbits are the circular orbits for the latter case. The proposed analytical solutions are utilized in the derivation of the guidance laws for motion with a thrust arc. These solutions allow us to compute the guidance commands for any given point of this arc connecting two terminal points of interest. The guidance laws for an extremal transfer between two elliptical orbits using only one intermediate-thrust arc are derived. [View Full Paper]

AAS 13 – 304

Sequential Convex Programming for Impulsive Transfer Optimization in Multibody Systems

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

This paper describes the development of a rapid local optimizer for minimum fuel impulsive transfers in multibody and higher order gravity systems. This Sequential Convex Programming process involves solving approximate convex problems and using differential correction to restore continuity. State transition matrices of arcs in the nonlinear system are used to derive the linear equality constraints and convex cost function of the approximation. Dynamic trust regions and other constraints are also shown to be convex. The exact solution of the resulting subproblem is found using existing convex solvers. Performance is compared to existing methods and is seen to be fast and robust.
[View Full Paper]

AAS 13 – 305

Indirect Optimization of Low-Thrust Earth Escape Trajectories

Hao Huang and **Chao Han**, School of Astronautics, Beihang University, Beijing, China; **Qi Gong**, Applied Mathematics and Statistics, University of California, Santa Cruz, California, U.S.A.

Indirect optimization is used in this paper to compute fuel-optimal earth escape trajectory. By shooting backward in time we convert the unknowns from initial Lagrange multipliers to orbit states at the final time. The three-dimensional long-time fuel-optimal escape trajectory with control constraint is designed by first solving a two-dimensional short-time fuel-optimal escape trajectory without control constraint; then using a curve fitting technique to generate initial guess for the final state. This accuracy and efficiency of the proposed method is demonstrated on a low thrust escape trajectory optimization problem. [View Full Paper]

SESSION 12:
SPECIAL SESSION: MARS SCIENCE LABORATORY (MSL) II
Chair: Dr. Gerhard Kruizinga, Jet Propulsion Laboratory

AAS 13 – 306

Assessment of the Reconstructed Aerodynamics of the Mars Science Laboratory Entry Vehicle

Mark Schoenenberger, **Artem Dyakonov** and **David Way**, NASA Langley Research Center, Hampton Virginia, U.S.A.; **John Van Norman**, **Chris Karlgaard** and **Prasad Kutty**, Analytical Mechanics Associates, Hampton, Virginia, U.S.A.

On August 5, 2012, the Mars Science Laboratory (MSL) entry vehicle successfully entered Mars atmosphere, flying a guided entry until parachute deploy. The Curiosity rover landed safely in Gale crater upon completion of the entry, descent, and landing sequence. This paper compares the aerodynamics of the entry capsule extracted from onboard flight data, including Inertial Measurement Unit (IMU) accelerometer and rate gyro information, and heatshield surface pressure measurements. From the onboard data, static force and moment data has been extracted. This data is compared to preflight predictions. The information collected by MSL represents the most complete set of information collected during Mars entry to date. It allows the separation of aerodynamic performance from atmospheric conditions. The comparisons show the MSL aerodynamic characteristics have been identified and resolved to an accuracy better than the aerodynamic database uncertainties used in preflight simulations. A number of small anomalies have been identified and are discussed. This data will help revise aerodynamic databases for future missions and will guide computational fluid dynamics (CFD) development to improve predictions. [View Full Paper]

AAS 13 – 307

Mars Science Laboratory Entry, Descent, and Landing Trajectory and Atmosphere Reconstruction

Christopher D. Karlgaard, **Prasad Kutty** and **Jeremy Shidner**, Analytical Mechanics Associates, Hampton, Virginia, U.S.A.; **Mark Schoenenberger**, Atmospheric Flight and Entry Systems Branch, NASA Langley Research Center, Hampton Virginia, U.S.A.

On August 5th 2012, The Mars Science Laboratory entry vehicle successfully entered Mars' atmosphere and landed the Curiosity rover on its surface. A Kalman filter approach has been implemented to reconstruct the entry, descent, and landing trajectory based on all available data. The data sources considered in the Kalman filtering approach include the inertial measurement unit accelerations and angular rates, the terrain descent sensor, the measured landing site, orbit determination solutions for the initial conditions, and a new set of instrumentation for planetary entry reconstruction consisting of forebody pressure sensors, known as the Mars Entry Atmospheric Data System. These pressure measurements are unique for planetary entry, descent, and landing reconstruction as they enable a reconstruction of the freestream atmospheric conditions without any prior assumptions being made on the vehicle aerodynamics. Moreover, the processing of these pressure measurements in the Kalman filter approach enables the identification of atmospheric winds, which has not been accomplished in past planetary entry reconstructions. This separation of atmosphere and aerodynamics allows for aerodynamic model reconciliation and uncertainty quantification, which directly impacts future missions. This paper describes the mathematical formulation of the Kalman filtering approach, a summary of data sources and preprocessing activities, and results of the reconstruction. [View Full Paper]

AAS 13 – 308

Inertial Navigation Entry, Descent, and Landing Reconstruction Using Monte Carlo Techniques

Robert C. Blanchard, **Robert H. Tolson**, **Rafael A. Lugo** and **Lynn Huh**,
National Institute of Aerospace, Hampton Viginia, U.S.A.

A new method for performing entry, descent, and landing trajectory reconstruction is presented as an extension of the standard inertial navigation approach of integrating inertial navigation unit data. The method, Inertial Navigation Statistical Trajectory and Atmosphere Reconstruction (INSTAR), provides statistical uncertainties for the reconstructed trajectory parameters by incorporating inertial navigation and Monte Carlo dispersion techniques. It also permits the inclusion of redundant data by refining the dispersed trajectories with those that satisfy the redundant observations to within specified tolerances. The primary advantage of inertial navigation over typical existing filtering techniques is the independence from aerodynamic and atmospheric models. The INSTAR concept along with a demonstration using flight data from the recent Mars Science Laboratory mission is presented. Initial conditions and acceleration biases are dispersed from nominal using Monte Carlo techniques, and the subset of trajectories that land near the reference landing site are used to update initial conditions and acceleration biases and to obtain trajectory statistics. These biases are then compared to the acceleration biases observed in the flight data. Eventually, the process will extend to other redundant data types and to atmosphere reconstruction, a process that relies on trajectory parameters and their uncertainties. [View Full Paper]

AAS 13 – 309

Preliminary Statistical Trajectory and Atmosphere Reconstruction of MSL Entry, Descent, and Landing

Soumyo Dutta and **Robert D. Braun**, Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.

On August 5, 2012, the Mars Science Laboratory spacecraft landed the heaviest payload on Mars using the largest aeroshell and supersonic parachute ever used by a planetary entry mission. Moreover, an innovative Sky Crane landing system was utilized to softly and accurately place the science payload on the ground near the desired target. The spacecraft recorded inertial measurement unit data and radar altimeter measurements during its descent through the Martian atmosphere and the aeroshell was also instrumented with flush atmospheric data system sensors that allow for the reconstruction of the vehicle's pressure distribution and freestream atmospheric conditions. This paper shows the preliminary results of the vehicle's trajectory and atmosphere reconstruction using a statistical estimation methodology that utilizes an extended Kalman filter. This method has been demonstrated with simulated Mars entry data in the past, and has the capability of simultaneously estimating the parameters and their uncertainties using the initial state covariance and measurement uncertainties. [View Full Paper]

AAS 13 – 310

The Mars Science Laboratory (MSL) Entry, Descent and Landing Instrumentation (MEDLI) Hardware

Michelle M. Munk, **Alan Little** and **Chris Kuhl**, NASA Langley Research Center, Hampton Virginia, U.S.A.; **Deepak Bose**, NASA Ames Research Center, Moffett Field, California, U.S.A.; **Jose Santos**, Sierra Lobo, Inc., NASA Ames Research Center, Moffett Field, California, U.S.A.

The Mars Science Laboratory (MSL) Entry, Descent and Landing Instrumentation (MEDLI) hardware was a first-of-its-kind sensor system that gathered engineering data from the MSL heatshield during Mars entry on August 6, 2012. MEDLI measured pressure and temperature, each at seven discrete locations determined by aerodynamicists and aerothermodynamicists. In this paper we will present a pictorial history and description of the MEDLI hardware, its requirements, and the unique aspects of the testing performed to qualify the hardware for the MSL mission environments. We will also discuss lessons learned and specific challenges in design and testing that may aid other instrumentation systems in decision-making. [View Full Paper]

AAS 13 – 311

A Reconstruction of Aerothermal Environment and Thermal Protection System Response of the Mars Science Laboratory Entry Vehicle

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An initial assessment and reconstruction of Mars Science Laboratory (MSL) entry aerothermal environment and thermal protection system (TPS) response is performed using the on-board instrumentation suite called MSL Entry, Descent, and Landing Instrumentation (MEDLI). The analysis is performed using the current best estimated trajectory. The MEDLI suite in part provides in-depth temperature measurements at seven locations on the heatshield. The temperature data show the occurrence of boundary layer transition to turbulence on the leeside forebody of the entry vehicle. The data also suggest that the TPS recession is lower than nominal model predictions using diffusion limited surface oxidation. The model predictions of temperatures show an underprediction in the stagnation and apex regions, and an overprediction in the leeside region. An estimate of time-varying aeroheating using an inverse reconstruction technique is also presented. The reconstructed aeroheating is sensitive to the choice of a recession model. [View Full Paper]

AAS 13 – 312

UHF Relay Performance During the Entry Descent and Landing of the Mars Science Laboratory

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This paper discusses the MSL telecommunications configuration for UHF relay data during EDL, as well as the configuration of NASA's Mars Reconnaissance Orbiter and Mars Odyssey. Actual link performance will be compared to *a priori* predictions including signal strength, Doppler shift, UHF plasma blackout, and the range and angles between MSL and UHF relay assets. Predictions were generated using telecom link budgets and models developed at JPL. These data were also integrated into MSL's primary end-to-end EDL performance simulation, NASA Langley's Program to Optimize Simulated Trajectories II (POST2), which enabled telecom predictions based on Monte Carlo results of EDL simulations. [View Full Paper]

AAS 13 – 313

Mars Science Laboratory Post-Landing Location Estimation Using POST2 Trajectory Simulation

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The Mars Science Laboratory (MSL) Curiosity rover landed safely on Mars August 5th, 2012 at 10:32 PDT, Earth Received Time. Immediately following touchdown confirmation, best estimates of position were calculated to assist in determining official MSL locations during entry, descent and landing (EDL). Additionally, estimated balance mass impact locations were provided and used to assess how predicted locations compared to actual locations. For MSL, the Program to Optimize Simulated Trajectories II (POST2) was the primary trajectory simulation tool used to predict and assess EDL performance from cruise stage separation through rover touchdown and descent stage impact. This POST2 simulation was used during MSL operations for EDL trajectory analyses in support of maneuver decisions and imaging MSL during EDL. This paper presents the simulation methodology used and results of pre/post-landing MSL location estimates and associated imagery from Mars Reconnaissance Orbiter's (MRO) High Resolution Imaging Science Experiment (HiRISE) camera. To generate these estimates, the MSL POST2 simulation nominal and Monte Carlo data, flight telemetry from onboard navigation, relay orbiter positions from MRO and Mars Odyssey and HiRISE generated digital elevation models (DEM) were utilized. A comparison of predicted rover and balance mass location estimations against actual locations are also presented.
[View Full Paper]

AAS 13 – 314
(Paper Withdrawn)

AAS 13 – 422

Entry System Design and Performance Summary for the Mars Science Laboratory Mission

Allen Chen and **Paul Brugarolas**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena California, U.S.A.; **Robin Beck**, NASA Ames Research Center, Moffett Field, California, U.S.A.; **Karl Edquist**, **Mark Schoenenberger** and **David Way**, NASA Langley Research Center, Hampton Virginia, U.S.A.; **Gavin Mendeck**, NASA Johnson Space Center, Houston, Texas, U.S.A.

While the Sky Crane portion of Mars Science Laboratory's (MSL) Entry, Descent, and Landing (EDL) system draws well-deserved attention as the iconic image of the landing, the entry segment is at least an equally harrowing part of the journey where a multitude of opportunities for failure exist. Over 99% of the spacecraft's kinetic energy is dissipated during entry as the spacecraft goes from over 5.8 km/s to approximately 400 m/s; all before the use of the supersonic parachute or the descent engines in powered flight. The entry vehicle had to survive aerothermal heating and considerable aerodynamic deceleration (up to 15 Earth g's), all while autonomously executing hypersonic and supersonic maneuvering to target the landing site and increase altitude and timeline margins. This paper provides an overview of the entry segment environment, events, and designed capability. It also summarizes Curiosity's as flown entry performance on the night of August 5th as reconstructed by the flight team. [View Full Paper]

SESSION 13: ORBITAL DYNAMICS AND SPACE ENVIRONMENT I
Chair: John Seago, Analytical Graphics, Inc.

AAS 13 – 315

Spacecraft Explosion Event Characterization Using Correlated Observations

Masahiko Uetsuhara and **Toshiya Hanada**, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka, Japan; **Toshifumi Yanagisawa**, Innovative Technology Research Center, JAXA, Chofu, Tokyo, Japan; **Yukihito Kitazawa**, Space Development Department, IHI Corporation, Koto-ku, Tokyo, Japan

This paper aims to characterize a spacecraft explosion event using correlated observations. Outcomes of the characterization measure will enable us to make current space situational awareness accurate, and to predict realistic future space situations. An event to be characterized in this paper is a breakup of the Titan 3C Transtage (1968-081E) exploded in the geostationary region. Characteristics to be evaluated include delta-velocity given to each fragment though the event, and a size distribution of the breakup fragments. This paper also discusses how effective the evaluated characteristics will contribute to re-visiting observation plans for the breakup fragments.
[View Full Paper]

AAS 13 – 316

Evolution of Angular Velocity for Space Debris as a Result of YORP

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

The Yarkovsky-O'Keefe-Raszvieskii-Paddack (YORP) effect has been well studied for asteroids. This paper analyzes the effects of YORP on the angular velocity of objects in Earth orbit. A semi-analytic solution to find the averaged Fourier coefficients defining the total moment on a body as a result of YORP is derived. This solution is used to explore the rate of change of a space debris like body's angular velocity. Solutions of the analytical theory are compared with numerical integrations. The implications of this effect for defunct satellites are discussed. [View Full Paper]

AAS 13 – 317

Coupled Orbit-Attitude Motion of High Area-to-Mass Ratio (HAMR) Objects Including Self-Shadowing

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This paper shows the effect of self-shadowing on the coupled attitude-orbit dynamics of objects with high area-to-mass ratios (HAMR) in simulating standard multi layer insulation materials (MLI) as tilted single rigid sheets. The coupled orbit-attitude perturbations of solar radiation pressure and Earth gravity field are taken into account. The results are compared to the attitude-orbit dynamics, when neglecting self-shadowing effects. An averaged physical shadow-map model is developed and compared to the full self-shadowing simulation. Accuracy considerations are made and the effect of a chosen tessellation is shown. [View Full Paper]

AAS 13 – 318
(Paper Withdrawn)

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(Paper Withdrawn)

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(Paper Withdrawn)

AAS 13 – 322
(Paper Withdrawn)

AAS 13 – 323

Preliminary Simulation for Light Curves of Rocket Body in LEO

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Orbital debris has become an inevitable problem for the future space exploration, and spacecraft is suggested to remove orbital debris. To fulfill this mission, you need to know target's attitude motion when installing a mitigation-related device. To support, we developed a simulator of orbit, attitude, and light curve to see how an object behaves. This paper presents a process to simulate virtual rocket body's observation in LEO assuming an existing telescope in Kyushu University, and to estimate the triaxial ratio, the spin axis, and the shape model. The real observation is supposed to be held in the near future. [View Full Paper]

AAS 13 – 324

(Paper Withdrawn)

AAS 13 – 465

The Equations of Relative Motion in the Orbital Reference Frame

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The analysis of relative motion of two spacecraft in Earth-bound orbits is usually carried out on the basis of simplifying assumptions. In particular, the reference spacecraft is assumed to follow a circular orbit, in which case the equations of relative motion are governed by the well-known Hill-Clohessy-Wiltshire (HCW) equations. Circular motion is not, however, a solution when the Earth's flattening is accounted for, except for equatorial orbits, where in any case the acceleration term is not Newtonian. Several attempts have been made to account for the J_2 effects, either by ingeniously taking advantage of their differential effects, or by cleverly introducing ad-hoc terms in the equations of motion on the basis of geometrical analysis of the J_2 perturbing effects. Analysis of relative motion about an unperturbed elliptical orbit is the next step in complexity. Relative motion about a J_2-perturbed elliptic reference trajectory is clearly a challenging problem, which has received little attention. All these problems are based on either the HCW equations for circular reference motion, or the de Vries/Tschauner-Hempel equations for elliptical reference motion, which are both approximate versions of the exact equations of relative motion. The main difference between the exact and approximate forms of these equations consists in the expression for the angular velocity and the angular acceleration of the rotating reference frame with respect to an inertial reference frame. The rotating reference frame is invariably taken as the local orbital frame, i.e., the RTN frame generated by the radial, the transverse, and the normal directions along the primary spacecraft orbit. Some authors have tried to account for the non-constant nature of the angular velocity vector, but have limited their correction to a mean motion value consistent with the J_2 perturbation terms. However, the angular velocity vector is also affected in direction, which causes precession of the node and the argument of perigee, i.e., of the entire orbital plane. Here we provide a derivation of the exact equations of relative motion by expressing the angular velocity of the RTN frame in terms of the state vector of the reference spacecraft. As such, these equations are completely general, in the sense that the orbit of the reference spacecraft need only be known through its ephemeris, and therefore subject to any force field whatever. It is also shown that these equations reduce to either the Clohessy-Wiltshire, or the HCW equations, depending on the level of approximation. The explicit form of the equations of relative motion with respect to a J_2-perturbed reference orbit is also introduced.
[View Full Paper]

AAS 13 – 486

The Mean-Solar-Time Origin of Universal Time and UTC

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P. Kenneth Seidelmann, Astronomy Department, University of Virginia, Charlottesville, Virginia, U.S.A.

Universal Time is the measure of Earth rotation that serves as the astronomical basis of civil timekeeping. Since the end of the 19th century, Universal Time has been maintained to preserve continuity with Newcomb's mean solar time at Greenwich. Here, the concept of a fictitious mean sun is revisited and compared with UT1. Simulations affirm that Universal Time has separated from Newcomb's mean sun by approximately (1/365) ΔT as predicted by theory. The disparity is about 0.2^s presently, which is much less than the $\pm 0.9^s$ differences allowed between UT1 and UTC, the atomic realization of mean solar time used for civil timekeeping. [View Full Paper]

AAS 13 – 488

DROMO Propagator Revisited

H. Urrutxua, **M. Sanjurjo-Rivo** and **J. Peláez**, Space Dynamics Group (SDG-UPM), ETSI Aeronáuticos, Technical University of Madrid (UPM), Madrid, Spain

In this paper we carried out a different deduction of the DROMO propagator, underlining its close relation with the Hansen ideal frame concept, and also the similarities and the differences with the theory carried out by Deprit in the paper "Ideal elements for perturbed keplerian motions" (*Journal of Research of the National Bureau of Standards*. Sec. B: Math. Sci., 79B, No. 1-2:1—15, 1975 Paper 79B1\&2—416). Simultaneously we introduce some improvements in the formulation that leads to a more synthetic propagator. [View Full Paper]

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(Paper Withdrawn)

AAS 13 – 490

Exploring The Impact of a Three-Body Interaction Added to the Gravitational Potential Function in the Restricted Three-Body Problem

Natasha Bosanac and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Ephraim Fischbach**, Department of Physics, Purdue University, West Lafayette, Indiana, U.S.A.

Many binary star systems (e.g., pulsar-white dwarf) are known to possess significantly smaller companions, such as an exoplanet, in orbit about the binary. In this investigation, the dynamical environment near the binary is modeled using a three-body interaction added to the inverse-square pairwise gravitational forces in the circular, restricted three-body problem (CR3BP), given a mass ratio of 0.3. This additional force contribution is assumed to depend inversely on the product of the distances between the three bodies. Frequency analysis is used to characterize the effect of this three-body interaction on periodic and quasi-periodic orbits in the exterior region for a large mass ratio binary. Sufficiently scaled attractive three-body interactions appear to induce period-multiplying bifurcations, with a low multiplicative factor, along families of periodic orbits, an effect that is not reproducible using large mass ratios in the range [0:2, 0:4] in the CR3BP. Repulsive three-body interactions appear to impact the formation of families of periodic orbits, influencing the location of stable and unstable orbits within a periodic orbit island chain. In addition, repulsive interactions influence the openings of the Lagrange point gateways, as compared with the CR3BP. [View Full Paper]

SESSION 14: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL I

Chair: Dr. Yanping Guo, Applied Physics Laboratory

AAS 13 – 325

The Deep Space Atomic Clock: Ushering in a New Paradigm for Radio Navigation And Science

Jill Seubert, **Todd Ely**, **John Prestage** and **Robert Tjoelker**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Deep Space Atomic Clock (DSAC) mission will demonstrate the on-orbit performance of a high-accuracy, high-stability miniaturized mercury ion atomic clock during a year-long experiment in Low Earth Orbit. DSAC's timing error requirement provides the frequency stability necessary to perform deep space navigation based solely on one-way radiometric tracking data. Compared to a two-way tracking paradigm, DSAC-enabled one-way tracking will benefit navigation and radio science by increasing the quantity and quality of tracking data. Additionally, DSAC also enables fully-autonomous onboard navigation useful for time-sensitive situations. The technology behind the mercury ion atomic clock and a DSAC mission overview are presented. Example deep space applications of DSAC, including navigation of a Mars orbiter and Europa flyby gravity science, highlight the benefits of DSAC-enabled one-way Doppler tracking.
[View Full Paper]

AAS 13 – 326

Flight Testing of Trajectories Computed by G-Fold: Fuel Optimal Large Divert Guidance Algorithm for Planetary Landing

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G-FOLD, Guidance for Fuel Optimal Large Divert, is an algorithm that is developed to compute, onboard in real-time, fuel optimal trajectories for large divert maneuvers necessary for planetary pinpoint or precision landing. The algorithm incorporates all relevant mission constraints and computes the global optimal trajectory. It is based on a mathematical result known as "lossless convexification" of the associated optimal control problem, which allowed us to formulate the problem as a convex optimization problem and to guarantee obtaining the global optimal solution when a feasible solution exists. Hence the algorithm ensures that all physically achievable diverts are also computable in real-time. This paper reports the first three flight test results of G-FOLD generated trajectories. The goal of these tests were to test pre-flight computed G-FOLD trajectories to demonstrate that they are computed with relevant mission constraints and appropriate vehicle dynamics accounted for. The results showed good agreement with the desired ideal trajectories with mismatches below expected bounds, which validated that the desired outcome that the trajectories were computed by using the right problem description and the resulting trajectories are flyable. [View Full Paper]

AAS 13 – 327
(Paper Withdrawn)

AAS 13 – 328

Multiple Sliding Surface Guidance for Planetary Landing: Tuning and Optimization Via Reinforcement Learning

Daniel R. Wibben, **Brian Gaudet** and **Roberto Furfaro**, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.;
Jules Simo, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, United Kingdom.

The problem of achieving pinpoint landing accuracy in future space missions to extra-terrestrial bodies such as the Moon or Mars presents many challenges, including the requirements of higher accuracy and more flexibility. These new challenges may require the development of novel and more advanced guidance algorithms. Conventional guidance schemes, which generally require a combination of off-line trajectory generation and real-time, trajectory tracking algorithms, have worked well in the past but may not satisfy the more stringent and difficult landing requirements imposed by future mission architectures to bring landers very near to specified locations. In this paper, a novel non-linear guidance algorithm for planetary landing is proposed and analyzed. Based on Higher-Order Sliding Control (HOSC) theory, the Multiple Sliding Surface Guidance (MSSG) algorithms has been specifically designed to take advantage of the ability of the system to reach the sliding surface in a finite time. The high control activity seen in typical sliding controllers is avoided in this formulation, resulting in a guidance law that is both globally stable and robust against unknown, but 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 point on the planet's surface without the need for calculation of multiple reference trajectories. However, after initial analysis, it has been seen that the performance of MSSG is very sensitive to the choice in guidance gains. MSSG generated trajectories have been compared to an optimal solution to begin an investigation of the relationship between the optimality and performance of MSSG and the selection of the guidance parameters. A full study has been performed to investigate and tune the parameters of MSSG utilizing reinforcement learning in order to truly optimize the performance of the MSSG algorithm. Results show that the MSSG algorithm can indeed generate trajectories that come very close to the optimal solution in terms of fuel usage. A full comparison of the trajectories is included, as well as a further study examining the capability of the MSSG algorithm under perturbed conditions using the optimized set of parameters. [View Full Paper]

AAS 13 – 329

Optimal Lunar Landing and Retargeting Using a Hybrid Control Strategy

Daniel R. Wibben and **Roberto Furfaro**, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.;
Ricardo G. Sanfelice, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona, U.S.A.

A novel non-linear spacecraft guidance scheme utilizing a hybrid controller for pinpoint lunar landing and retargeting is presented. The development of this algorithm is motivated by a) the desire to satisfy more stringent landing accuracies required by future lunar mission architectures, and b) the interest in analyzing the ability of the system to perform retargeting maneuvers during the descent to the lunar surface. Based on Hybrid System theory, the proposed Hybrid Guidance algorithm utilizes both a global and local controller to bring the lander safely to the desired target on the lunar surface with zero velocity in a finite time. The hybrid system approach utilizes the fact that the logic and behavior of switching guidance laws is inherent in the definition of the system. The presented case of a hybrid system utilizes a global controller that implements an optimal guidance law augmented with a sliding mode to bring the lander from an initial state to a predetermined reference trajectory and an LQR-based local controller to bring the lander to the desired point on the lunar surface. The individual controllers are shown to be stable in their respective regions. The behavior and performance of the Hybrid Guidance Law (HGL) is examined in a set of Monte Carlo simulations under realistic conditions. Results demonstrate the capability of the hybrid guidance law to reach the desired target point on the lunar surface with low residual guidance errors. Further, the Hybrid Guidance Law has been applied to the problem of retargeting in order to examine the performance of the algorithm under such conditions. [View Full Paper]

AAS 13 – 330

Navigating a Crewed Lunar Vehicle Using LiAISON

Jeffrey S. Parker, **Jason M. Leonard**, **Kohei Fujimoto**, **Ryan M. McGranaghan** and **George H. Born**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.; Rodney L. Anderson, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

This paper examines the benefits of navigating a crewed vehicle at the Moon using both ground tracking and satellite-to-satellite tracking, where the tracking satellite is stationed in a lunar halo orbit. Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) is a new technique that has been shown to dramatically improve the navigation of lunar satellites, libration orbiters, and Earth orbiting satellites using simple scalar satellite-to-satellite observations, such as range or Doppler. In this paper, LiAISON is applied to the problem of navigating a crewed vehicle in low lunar orbit. It has been found that adding LiAISON observations to a ground navigation solution improves the navigation enough to reduce the number of active ground tracking stations from six to three. [View Full Paper]

AAS 13 – 331

Constrained Station Change in GEO Using a Legendre Pseudo-Spectral Method

Seung Pil Kim and **Robert G. Melton**, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.

The algorithm for numerical approximation of the optimal control is formulated using a Legendre pseudo-spectral method to solve the problem of constrained station change in GEO. A collision avoidance term, which is included in the objective function as an integral form, is considered during transfer by specifying a maximum or minimum radius depending on whether the transfer is in the east or west-direction. Several east-and-west-direction station change transfer maneuvers are simulated; the histories of the states and control behavior are obtained and all the variables are found to be within feasible ranges. Multiple revolutions and large longitude station change cases are also demonstrated using this method. The transfer time is found to be only weakly affected by the initial thrust acceleration for the multi-revolution change cases. This method would be possible to implement using very low-thrust engines, in particular, by employing attitude control thrusters. [View Full Paper]

AAS 13 – 332

Optimal Trajectory Design for Aerobraking*

Ling Jiang, **Shijie Xu** and **Tong Chen**, Department of Aerospace Engineering, School of Astronautics, Beihang University, Beijing, China; **Yingzi He**, Science and Technology on Space Intelligent Control Laboratory, Beijing Institute of Control Engineering, Beijing, China

Aerobraking is an efficient aeroassisted technique that has been used successfully in recent Mars missions. However, trajectory design process is complicated yet time consuming with multiple passes through the atmosphere. A simple but effective design method to make this process easier is proposed. Firstly, perturbed classic element of orbit analysis is used to optimize of periapsis selection. After choosing the appropriate initial periapsis, an elaborate computational model is developed to simulate the trajectory. Simulation results show a significant reduction in the maximum control input and maximum heating rate. The method here can be used for reference to engineering application. [View Full Paper]

AAS 13 – 333

Research and Verification of Multi-Frequency Same Beam VLBI Based on General TT&C Signal

Lue Chen, **Geshi Tang**, **Songtao Han**, **Mei Wang** and **Huicui Liu**, Science and Technology on Aerospace Flight Dynamics Laboratory, Beijing Aerospace Control Center, Beijing, China; **Ling Jiang**, Department of Aerospace Engineering, School of Astronautics, Beihang University, Beijing, China

The relative measurement of two spacecraft is very important for multi-spacecraft cooperative flight mission and improving spacecraft's orbit determination accuracy for space science exploration research. The method of multi-frequency same beam VLBI utilizing general Tracking, Telemetry and Control (TT&C) signal is proposed to implement two spacecraft's relative measurement in this paper. Based on the mathematical calculation of the difference phase delay, the validity of this method is verified by simulation. A model modification method of differential delay measurement error is proposed too. Utilizing the multi-frequency information of the general TT&C signal of the two spacecraft, the simulation results shows that picoseconds error level differential phase delay is obtained. This could provide a useful measurement technology for relative navigation and position between two spacecraft in deep space mission.

[View Full Paper]

AAS 13 – 471

Analytical Guidance for Spacecraft Relative Motion Under Constant Thrust Using Relative Orbit Elements

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Thomas Alan Lovell, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

This paper introduces novel analytical guidance solutions for spacecraft relative motion considering continuous, on-off thrust, and using Relative Orbit Elements as a geometrical representation of the dynamics. The solutions provide the relative state vector at any given time, accommodating any thrust magnitude along the three directions of the relative frame, as well as generic activation times and durations. Relative Orbit Elements geometrically interpret key aspects of the relative motion, including for example, the relative ellipse size, and the evolution of its center in time. The new solutions provide the guidance designer with a direct visualization of the thrust effects on the relative motion geometry, offering new possibilities for analytical guidance in the presence of continuous thrust engines, such as low thrust engines on nano-spacecraft. The paper presents the analytical solutions, and tests their effectiveness using a sample guidance thrust profile based on input-shaping, previously developed by one of the authors using classical Cartesian coordinates. The use of Relative Orbit Elements shows substantial benefits and added simplicity with respect to Cartesian-based approaches.

[View Full Paper]

SESSION 15: DYNAMICAL SYSTEMS THEORY
Chair: Dr. Kathleen C. Howell, Purdue University

AAS 13 – 334

Leveraging Resonant Orbit Manifolds to Design Transfers Between Libration Point Orbits in Multi-Body Regimes

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Resonant orbits have been widely employed in mission design for planetary flyby trajectories (JEO) and, more recently, as a source of long-term stability (IBEX). Yet, resonant orbits have not been explored extensively as transfer mechanisms between non-resonant orbits in multi-body systems. To highlight the benefit of employing resonant orbits for transfers and given the increased interest in employing libration point orbits for a variety of purposes, 2D and 3D transfers from LEO to the vicinity of the Earth-Moon libration points via resonant arcs are presented. Solutions are efficiently generated in the circular restricted three-body model and transitioned to a higher-fidelity model for validation. Direct optimization can further reduce the propellant requirements and a system translation technique is defined to add versatility to the proposed transfer design process, allowing for the quick translation of Earth-Moon transfers to other three-body systems. [View Full Paper]

AAS 13 – 336

Examining the Learning Rate in Iterative Learning Control Near the End of the Desired Trajectory

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Iterative learning control (ILC) aims to achieve zero tracking error following a finite time trajectory that is repeated, each time starting from the same initial condition. Spacecraft applications include repeated tracking maneuvers of fine pointing equipment. Three important ILC laws are examined, including a contraction mapping law, a partial isometry law, and an ILC law based on quadratic cost adjustment of the learning rate. It is shown that each of these laws exhibits a phenomenon of poor convergence of the control action near the end of the finite time trajectory. Methods analogous to the use of terminal penalty functions in quadratic cost feedback control design for finite time trajectories are studied. But each is seen to be unable to address the problem. It is suggested that one can extend the desired trajectory so that the poor performance occurs after the end of the finite time problem. Another method prefilters the desired trajectory through the ILC law and uses the resulting trajectory as the initial command to the feedback control system. It is seen to be particularly effective. There are situations in which one cannot apply either of these methods, but when they can be applied they result in improved tracking error performance. [View Full Paper]

AAS 13 – 337

Linear State Representations for Identification of Bilinear Discrete-Time Models by Interaction Matrices

Francesco Vicario, Department of Mechanical Engineering, Columbia University New York, New York, U.S.A.; **Minh Q. Phan**, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, U.S.A.; **Raimondo Betti**, Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, New York, U.S.A.; **Richard W. Longman**, Department of Mechanical Engineering and Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, New York, U.S.A.

Bilinear systems can be viewed as a bridge between linear and nonlinear systems, providing a promising approach to handle various nonlinear identification and control problems. This paper provides a formal justification for the extension of interaction matrices to bilinear systems and uses them to express the bilinear state as a linear function of input-output data. Multiple representations of this kind are derived, making it possible to develop an intersection subspace algorithm for the identification of discrete-time bilinear models. The technique first recovers the bilinear state by intersecting two vector spaces that are defined solely in terms of input-output data. The new input-output-to-state relationships are also used to extend the Equivalent Linear Model method for bilinear system identification. Among the benefits of the proposed approach, it does not require data from multiple experiments, and it does not impose specific restrictions on the form of input excitation. [View Full Paper]

AAS 13 – 338

Short and Long Term Closed Orbit Design in Sun-Earth Elliptic-Restricted 3-Body Problem

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In this study, we show the multiple revolution orbits design in Elliptic Restricted 3-Body Problem (ER3BP) of Sun, Earth and a particle 3-body system. For the deep-space observation, the location around L2 point is suitable because of the wide field of view to the outer space. In near future, some missions are planned to be putted into the Sun-Earth L2 point orbits. Depending on the mission requirements, the periodic orbits may not be the necessary condition. Therefore, the multiple revolution orbit closed in configuration space under arbitrary conditions are considered. Additionally, a preliminary calculation of the orbit maintenance is provided. [View Full Paper]

AAS 13 – 339

Preliminary Design Considerations for Access and Operations in Earth-Moon L_1/L_2 ORBITS

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Within the context of manned spaceflight activities, Earth-Moon libration point orbits could support lunar surface operations and serve as staging areas for future missions to near-Earth asteroids and Mars. This investigation examines preliminary design considerations including Earth-Moon L_1/L_2 libration point orbit selection, transfers, and stationkeeping costs associated with maintaining a spacecraft in the vicinity of L_1 or L_2 for a specified duration. Existing tools for multi-body trajectory design, dynamical systems theory, and orbit maintenance are leveraged in this analysis to explore end-to-end concepts for manned missions to Earth-Moon libration points. [View Full Paper]

AAS 13 – 340

Optimal Impulsive Manifold-Based Transfers With Guidance to Earth-Moon L_1 Halo Orbits

William Anthony, **Annie Larsen** and **Eric A. Butcher**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.

An optimization method combining genetic algorithms, differential correction, and primer vector theory is employed for designing fuel optimal 2-impulse transfers from low earth orbit or geostationary orbit to a halo orbit about the Earth-Moon L_1 libration point using the stable manifold of the halo orbit. All transfers require one maneuver to leave LEO or GEO and a second maneuver to transfer onto the stable manifold. The trajectories obtained have total ΔV's of 3.61 and 1.14 km/s respectively. An LQR based guidance scheme is presented which maintains the spacecraft on the stable manifold in the presence of injection errors in burn magnitude and direction using a variable low continuous thrust engine. Monte Carlo analyses are conducted to further demonstrate the effectiveness of the guidance scheme. The total ΔV costs to use the guidance scheme averages 14.385 m/s for transfers from LEO and 6.54 m/s for transfers from GEO, when a thrust magnitude Gaussian dispersion with $1\sigma = 1\%$ is combined with in-plane and out-of-plane thrust direction Gaussian dispersions with $1\sigma = 1$ degree error. The guidance is also implemented assuming a limit to the continuous thrust.
[View Full Paper]

AAS 13 – 341

Abort Options for Human Missions to Earth-Moon Halo Orbits

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Abort trajectories are optimized for human halo orbit missions about the translunar libration point (L_2), with an emphasis on the use of free return trajectories. Optimal transfers from outbound free returns to L_2 halo orbits are numerically optimized in the four-body ephemeris model. Circumlunar free returns are used for direct transfers, and cislunar free returns are used in combination with lunar gravity assists to reduce propulsive requirements. Trends in orbit insertion cost and flight time are documented across the southern L_2 halo family as a function of halo orbit position and free return flight time. It is determined that the maximum amplitude southern halo incurs the lowest orbit insertion cost for direct transfers but the maximum cost for lunar gravity assist transfers. The minimum amplitude halo is the most expensive destination for direct transfers but the least expensive for lunar gravity assist transfers. The on-orbit abort costs for three halos are computed as a function of abort time and return time. Finally, an architecture analysis is performed to determine launch and on-orbit vehicle requirements for halo orbit missions. [View Full Paper]

AAS 13 – 469

Second Order Nonlinear Initial Value Solution for Relative Motion Using Volterra Theory

Mary T. Stringer and **Brett Newman**, Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, Virginia, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.; **Ashraf Omran**, Engineering Analyst, Systems Modeling, CNH-Fiat Industrial, Burr Ridge, Illinois, U.S.A.

Application of Volterra multi-dimensional convolution theory to the nonlinear J_2 perturbed circular relative motion initial value problem is considered in this paper. A complete analytic second order solution for the three-dimensional time dependent relative motion positions in the unperturbed case is generated, and the framework for the perturbed case is documented. Deputy closed-form response expressions are in terms of linear, quadratic, and bilinear combinations of the initial conditions and the chief orbital elements. The Clohessy-Wiltshire linear solution is found to be embedded within the broader nonlinear solution, and the additional nonlinear terms are used to examine and reveal characteristics of the nonlinear relative motion, including amplification, attenuation, and/or reversal of the in-track drift rate. The strengths between various excitation sources including initial positions vs. rates, radial vs. in-track vs. cross-track sources, and linear vs. nonlinear mechanisms are explicit in the formulation. One case is highlighted where the linear propagation and new solution predict opposite intrack drift directions. For the investigated example, accuracy of the second order solution improves significantly on that for the linear solution. [View Full Paper]

AAS 13 – 470

Second Order Nonlinear Boundary Value Solution for Relative Motion Using Volterra Theory

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Application of Volterra multi-dimensional convolution theory to the nonlinear unperturbed circular relative motion boundary value problem is considered in this paper. A solution for the initial three-dimensional relative velocity that executes a transfer between specified three-dimensional initial and final relative positions in a specified time period is investigated. A previously generated analytic second order solution for the time dependent relative motion deputy positions in terms of linear, quadratic, and bilinear combinations of the initial conditions and the chief orbital elements is used as the basis for the solution. This framework converts the differential boundary value problem to an algebraic one. The resulting nonlinear equations are examined analytically and numerically in various ways to reveal solution characteristics for several cases. Governing relations are analytically structured in a triple variable, double variable, or single variable formulation. Solution multiplicity and visualization using these optional formulations are discussed. The Clohessy-Wiltshire linear boundary value solution is found to be embedded within the broader nonlinear solution. A family of transfer trajectories parameterized by the transfer time are analyzed numerically, and high sensitivity is discovered near the orbital half-period. For the investigated cases, accuracy of the second order solution improves significantly on that for the linear solution.
[View Full Paper]

AAS 13 – 493

Tour Design Using Resonant Orbit Heteroclinic Connections in Patched Circular Restricted Three-Body Problems

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It is increasingly desirable to incorporate multi-body effects in tour design early in the process to make use of these effects and potentially discover new solutions. Flybys have previously been designed using the heteroclinic connections of resonant orbits in the circular restricted three-body problem (CRTBP), but tour design often requires the consideration of additional moons, especially within the Jovian system. In this study, the heteroclinic connections of multiple resonant orbits are chained together within separate CRTBP models to perform multiple flybys that advance through desired resonances. The aspects of patching these trajectories together are explored, and sample trajectories are computed. [View Full Paper]

SESSION 16: SPECIAL SESSION: DAWN
Chair: Dr. Shyam Bhaskaran, Jet Propulsion Laboratory

AAS 13 – 342

Ion Propulsion: An Enabling Technology for the Dawn Mission

Charles E. Garner, **Mark M. Rayman**, **Greg J. Whiffen**, **John R. Brophy** and **Steven C. Mikes**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Dawn mission, part of NASA's Discovery Program, has as its goal the scientific exploration of the two most massive main-belt asteroids, 4 Vesta, and the dwarf planet 1 Ceres. The Dawn spacecraft was launched from the Cape Canaveral Air Force Station on September 27, 2007 on a Delta-II 7925H-9.5 rocket that placed the 1218-kg spacecraft into an Earth-escape (heliocentic) trajectory with an escape velocity of 11 km/s. On-board the spacecraft is an ion propulsion system (IPS) developed at the Jet Propulsion Laboratory which will provide an additional delta-V of approximately 11 km/s for the heliocentric transfers to each body and for all orbit transfers including orbit capture/escape and transition to the various science orbits. Deterministic thrusting to Vesta began in December 2007 and concluded with orbit capture at Vesta in July 2011. The transfer to Vesta included a Mars gravity assist flyby in February 2009 that provided an additional delta-V of 2.6 km/s and was the only post-launch mission delta-V not provided by IPS. The IPS was used during the 14 months at Vesta for all science orbit transfers and then for Vesta escape. Deterministic thrusting for Ceres began in late August 2012 with a planned arrival date at Ceres in early 2015, whereupon IPS will be used for all science orbit transfers. As of January 2013 the IPS has been operated for approximately 28,000 hours, consumed approximately 280 kg of xenon, and provided a delta-V of approximately 7.5 km/s, the most post-launch delta-V of any spacecraft yet flown. IPS performance characteristics are very close to the expected performance based on analysis and testing performed pre-launch. Use of the IPS together with a medium-priced launch vehicle enabled this high delta-V mission to be performed within the Discovery Program cost cap. This paper provides an overview of the Dawn IPS and its mission operations through departure for Ceres. [View Full Paper]

AAS 13 – 343

Thrust Direction Optimization: Satisfying Dawn's Attitude Agility Constraints

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The science objective of NASA's Dawn Discovery mission is to explore the giant asteroid Vesta and the dwarf planet Ceres, the two largest members of the main asteroid belt. Dawn successfully completed its orbital mission at Vesta. The Dawn spacecraft has complex, difficult to quantify, and in some cases severe limitations on its attitude agility. The low-thrust transfers between science orbits at Vesta required very complex time varying thrust directions due to the strong and complex gravity and various science objectives. Traditional low-thrust design objectives (like minimum ΔV or minimum transfer time) often result in thrust direction time evolutions that cannot be accommodated with the attitude control system available on Dawn. This paper presents several new optimal control objectives, collectively called thrust direction optimization that were developed and turned out to be essential to the successful navigation of Dawn at Vesta. [View Full Paper]

AAS 13 – 344

Dawn Maneuver Design Performance at Vesta

D. W. Parcher, **M. Abrahamson**, **A. Ardito**, **D. Han**, **R. J. Haw**, **B. M. Kennedy**, **N. Mastrodemos**, **S. Nandi**, **R. S. Park**, **B. P. Rush**, **B. A. Smith**, **J. C. Smith**, **A. T. Vaughan** and **G. J. Whiffen**, Guidance Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Dawn spacecraft orbited the asteroid Vesta from July 16, 2011 to September 5, 2012, successfully accomplishing the four planned science orbits and two planned rotational characterization orbits. The lowest-altitude science orbit lasted four months, with 20 planned orbit maintenance maneuvers. Navigation results from Vesta demonstrate that the navigation plan was sufficient to achieve orbit delivery accuracy requirements. This paper compares the flown Dawn trajectory against the planned trajectory and expected maneuver dispersions. Understanding the effectiveness of the Vesta maneuver design plan is a key component of planning for operations at Ceres, the next destination for the Dawn mission. [View Full Paper]

AAS 13 – 345

Dawn Orbit Determination Team: Trajectory and Gravity Prediction Performance During Vesta Science Phases

Brian Kennedy, **Matt Abrahamson**, **Alessandro Ardito**, **Dongsuk Han**, **Robert Haw**, **Nicholas Mastrodemos**, **Sumita Nandi**, **Ryan Park**, **Brian Rush** and **Andrew Vaughan**, Guidance Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Dawn spacecraft was launched on September 27th, 2007. Its mission is to consecutively rendezvous with and observe the two largest bodies in the asteroid belt, Vesta and Ceres. It has already completed over a year's worth of direct observations of Vesta (spanning from early 2011 through late 2012) and is currently on a cruise trajectory to Ceres, where it will begin scientific observations in mid-2015. Achieving this data collection required careful planning and execution from all spacecraft teams. Dawn's Orbit Determination (OD) team was tasked with accurately predicting the trajectory of the Dawn spacecraft during the Vesta science phases, and also determining the parameters of Vesta to support future science orbit design. The future orbits included the upcoming science phase orbits as well as the transfer orbits between science phases. In all, five science phases were executed at Vesta, and this paper will describe some of the OD team contributions to the planning and execution of those phases.
[View Full Paper]

AAS 13 – 346

Dawn Orbit Determination Team: Trajectory Modeling and Reconstruction Processes at Vesta

Matthew J. Abrahamson, **Alessandro Ardito**, **Dongsuk Han**, **Robert Haw**, **Brian Kennedy**, **Nick Mastrodemos**, **Sumita Nandi**, **Ryan Park**, **Brian Rush** and **Andrew Vaughan**, Guidance Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Dawn spacecraft spent over a year in orbit around Vesta from July 2011 through August 2012. In order to maintain the designated science reference orbits and enable the transfers between those orbits, precise and timely orbit determination was required. Challenges included low-thrust ion propulsion modeling, estimation of relatively unknown Vesta gravity and rotation models, tracking data limitations, incorporation of real-time telemetry into dynamics model updates, and rapid maneuver design cycles during transfers. This paper discusses the dynamics models, filter configuration, and data processing implemented to deliver a rapid orbit determination capability to the Dawn project. [View Full Paper]

AAS 13 – 347

Dawn Orbit Determination Team: Modeling and Fitting of Optical Data at Vesta

Brian Kennedy, **Matt Abrahamson**, **Alessandro Ardito**, **Robert Haw**, **Nicholas Mastrodemos**, **Sumita Nandi**, **Ryan Park**, **Brian Rush** and **Andrew Vaughan**, Guidance Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Dawn spacecraft was launched on September 27th, 2007. Its mission is to consecutively rendezvous with and observe the two largest bodies in the main asteroid belt, Vesta and Ceres. It has already completed over a year's worth of direct observations of Vesta (spanning from early 2011 through late 2012) and is currently on a cruise trajectory to Ceres, where it will begin scientific observations in mid-2015. Achieving this data collection required careful planning and execution from all Dawn operations teams. Dawn's Orbit Determination (OD) team was tasked with reconstruction of the as-flown trajectory as well as determination of the Vesta rotational rate, pole orientation and ephemeris, among other Vesta parameters. Improved knowledge of the Vesta pole orientation, specifically, was needed to target the final maneuvers that inserted Dawn into the first science orbit at Vesta. To solve for these parameters, the OD team used radiometric data from the Deep Space Network (DSN) along with optical data reduced from Dawn's Framing Camera (FC) images. This paper will describe the initial determination of the Vesta ephemeris and pole using a combination of radiometric and optical data, and also the progress the OD team has made since then to further refine the knowledge of Vesta's body frame orientation and rate with these data.
[View Full Paper]

AAS 13 – 348

Recovering the Gravity Field of Vesta From Dawn

Sami Asmar, **Alex Konopliv**, **Ryan Park** and **Carol Raymond**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The successfully completed Dawn mission to asteroid Vesta has lead to the generation of a global solution of gravity measurements of degree and order 20. When correlated with a shape model derived from imaging, these data can constrain the interior structure from the crust to possible core. Utilizing precision spacecraft Doppler measurements and landmark tracking from framing camera images to measure the gravity field, the solution also yields the spin-pole location and rotation. The second-degree harmonics together with assumptions on obliquity or hydrostatic equilibrium determine the moments of inertia and constrain the core size and density. J2 parameter shows inconsistency with a homogenous density body. This paper describes the investigation development and its scientific results. [View Full Paper]

AAS 13 – 349

(Paper Withdrawn)

AAS 13 – 350

Spiraling Away from Vesta: Design of the Transfer from the Low to High Altitude Dawn Mapping Orbits

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Dawn has successfully completed its orbital mission at Vesta and is currently en route to an orbital rendezvous with Ceres in 2015. The longest duration and most complex portion of the Vesta departure trajectory was the transfer from the low to high altitude science orbit. This paper describes the design of this low-thrust trajectory optimized assuming a minimum-propellant mass objective. The transfer utilized solar-electric ion propulsion applied over 139 spacecraft revolutions about Vesta. Science drivers, operational constraints, and robustness to statistical uncertainties are addressed. The 45-day transfer trajectory was successfully implemented in early 2012.
[View Full Paper]

SESSION 17:
SPACE SITUATIONAL AWARENESS AND CONJUNCTION ANALYSIS I
Chair: Dr. Daniel J. Scheeres, University of Colorado

AAS 13 – 351

Collision Probability for Space Objects Using Gaussian Mixture Models

Vivek Vittaldev and **Ryan P. Russell**, The University of Texas at Austin, Texas, U.S.A.

Computation of space object collision probability plays a large role in the spacecraft community. The number of active satellites and debris is increasing day by day, which leads to a very realistic chance of a runoff. In general, the methods in practice for computing collision probability require that the uncertainty distributions be represented with a linearized position covariance; otherwise Monte Carlo simulations are required, which are computationally intensive. Our goal is to use Gaussian Mixture Models (GMMs) to improve collision probability computations. The method is a hybrid between the fast and commonly inaccurate linearized techniques and the slow but highly accurate Monte Carlo techniques. This paper represents a first step of the process, where the effects of velocity variations at close approach, typically assumed to be constant, are captured using GMM models. The results show improved probability predictions despite an almost trivial compute burden compared to a Monte Carlo method. The method naturally extends to capture the effects of non-Gaussian uncertainty distributions. We have also used trust region optimization in order to extend univariate splitting libraries out to 25 elements. [View Full Paper]

AAS 13 – 352

Determining a Probability-Based Distance Threshold for Conjunction Screening

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To reduce processing time, satellite conjunction prediction tools often employ methods to decrease the number of objects for consideration. Various economizing 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. For each pair that remains, the respective orbits are propagated to determine if the minimum distance between objects is below a preset screening threshold. When conjunction probability is to be used as a metric, the minimum distance threshold must be determined from the minimum acceptable probability threshold. This work develops an analytical approximation that relates maximum probability to a miss distance threshold, thereby ensuring that the screening distance is adequate for probability-based conjunction assessment. [View Full Paper]

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(Paper Withdrawn)

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(Paper Withdrawn)

AAS 13 – 355

Trajectory Error and Covariance Realism for Launch COLA Operations

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Non-uniform guidance and practices for Launch Collision Avoidance (LCOLA) among different NASA field centers (and the Air Force launch ranges) has prompted NASA Headquarters to commission a study to develop recommendations for standardizing the process and for suggested screening thresholds. The full study will be completed in early 2013, but the results for the initial phases are reported herein, namely an investigation of the accuracies of the pre-launch predicted trajectories and the realism of their associated covariances. The study determined that, for the Atlas V and Delta II launch vehicles, trajectory errors remain approximately an order of magnitude larger than General Perturbations (GP) satellite catalogue errors, confirming that it is not necessary to resort to a precision catalogue to perform LCOLA screenings. The associated launch covariances, which are large and had been thought to be conservatively sized, were found instead to be quite appropriately determined and fare well in covariance realism analyses. As such, the launch-related information feeding the LCOLA process will allow a durable calculation of the probability of collision and thus can serve as a reliable basis for LCOLA operations. [View Full Paper]

AAS 13 – 356

(Paper Withdrawn)

AAS 13 – 357

On-Board Estimation of Collision Probability for Cluster Flight

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Being able to detect and respond to potential collisions is a significant concern for satellite cluster flight. The accuracy and speed at which collision probability is estimated is a key factor in determining the minimum allowable closest approach distance between any two modules, and thus the total size of the cluster. Perhaps the simplest metric of collision probability is propagating the navigation state forward in time and calculating the closest approach distance. While this method has the advantages of being simple and easy to implement onboard, it does not take into account the uncertainty in the navigation state. A method is presented which takes into account both the state and state uncertainty to estimate collision probability. Additionally this method generates a range of values in which the true probability of collision will fall. The accuracy of this method is verified through Monte Carlo simulation. [View Full Paper]

AAS 13 – 358
(Paper Withdrawn)

AAS 13 – 359

Autonomy Architecture for a Raven-Class Telescope With Space Situational Awareness Applications

Ryan D. Coder and **Marcus J. Holzinger**, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.

This paper investigates possible autonomy architecture designs of a Raven-class telescope as applied to the tracking and high level characterization problem in Space Situational Awareness (SSA). Various levels of autonomy are defined and existing systems and capabilities are discussed. Telescope interactions with distributed sensor networks such as the Space Surveillance Network (SSN) are reviewed, and several relationships between autonomy and scheduling of telescopes are addressed. An autonomy architecture design for a Raven-class telescope is presented and future extensions are proposed. [View Full Paper]

AAS 13 – 360

A Geometric Analysis to Protect Manned Assets From Newly Launched Objects – COLA Gap Analysis

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A safety risk was identified for the International Space Station (ISS) by The Aerospace Corporation, where the ISS would be unable to react to a conjunction with a newly launched object following the end of the launch Collision Avoidance (COLA) process. Once an object is launched, there is a finite period of time required to track, catalog, and evaluate that new object as part of standard on-orbit COLA screening processes. Additionally, should a conjunction be identified, there is an additional period of time required to plan and execute a collision avoidance maneuver. While the computed prelaunch probability of collision with any object is extremely low, NASA/JSC has requested that all US launches take additional steps to protect the ISS during this “COLA gap” period. This paper details a geometric-based COLA gap analysis method developed by the NASA Launch Services Program to determine if launch window cutouts are required to mitigate this risk. Additionally, this paper presents the results of several missions where this process has been used operationally. [View Full Paper]

SESSION 18: ATTITUDE DETERMINATION, DYNAMICS AND CONTROL III
Chair: Dr. Don Mackison, University of Colorado

AAS 13 – 361
Greedy Tasking for Spacecraft Attitude Resource Sharing

Shawn C. Johnson and **Norman G. Fitz-Coy**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.; **Seth L. Lacy**, Space Vehicles Directorate, Air Force Research Laboratory, Albuquerque, New Mexico, U.S.A.

A greedy tasking approach to attitude resource sharing in fractionated spacecraft architectures is presented. One spacecraft possesses the capability to determine its inertial attitude and its relative attitude with respect to a network of receiving spacecraft. The receiving spacecraft require inertial attitude knowledge, but lack on-board attitude sensors. The resulting optimal tasking problem lacks separation in estimation and control, which motivates the greedy tasking approach. Covariance matrix norms and differential entropy are used as metrics for greedy tasking and are compared with a baseline Round-robin tasking. Simulations demonstrate the methods improvement in network-level attitude pointing accuracy over the baseline. [View Full Paper]

AAS 13 – 362
Q-Method Extended Kalman Filter

Renato Zanetti and **Thomas Ainscough**, Charles Stark Draper Laboratory, Houston, Texas, U.S.A.; **John Christian**, GNC Autonomous Flight Systems Branch, NASA Johnson Space Center, Houston, Texas, U.S.a.; **Pol D. Spanos**, Ryon Chair of Engineering, Rice University, Houston, Texas, U.S.A.

A new algorithm is proposed that smoothly integrates the non-linear estimation of the attitude quaternion using Davenport’s q-method and the estimation of nonattitude states through an extended Kalman filter. The new algorithm is compared to an existing similar one and the various similarities and differences are discussed. The validity of the proposed approach is confirmed by pertinent numerical simulations.
[View Full Paper]

AAS 13 – 363

Attitude Reconstruction Analysis of the Reentry Breakup Recorder

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The Reentry Breakup Recorder is a very small space vehicle that has its own power source and flight instruments. It was designed to capture reentry environmental data experienced by reentering spacecraft. It reenters the atmosphere with its host vehicle, records and stores environmental data, survives the breakup of the host vehicle, survives the aerothermal environment as a free flyer, and transmits its recorded data to a ground site via the Iridium network. REBR's attitude throughout the reentry period is needed to assess the performance of its heat shield and its aerodynamic stability. The low data rate of transmissions of accelerometer and rate gyro data presented a challenge due to stressing dynamic environment. This paper presents the methods used to reconstruct the REBR's attitude. Results of the analysis indicated that the attitude was reconstructed accurately with the exception of the extremely violent breakup period of the host vehicle. [View Full Paper]

AAS 13 – 364

Online Attitude Determination of a Passively Magnetically Stabilized Spacecraft

Roland Burton and **Stephen Rock**, Stanford University, Stanford, California, U.S.A.; **John Springmann** and **James Cutler**, University of Michigan, Ann Arbor, Michigan, U.S.A.

An online attitude determination filter is introduced that is capable of estimating the attitude of a passively magnetically stabilized spacecraft to within about five degrees accuracy using only an estimate of the solar vector. This filter enables nano satellites to perform onboard attitude determination even when no dedicated attitude sensors are installed, instead relying only on the electrical currents from body mounted solar panels. The online attitude filter is applied in post processing to orbital data from NASA Ames Research Center's O/OREOS and the University of Michigan's RAX-1 spacecraft. [View Full Paper]

AAS 13 – 365

Development of the Illinisat-2 Attitude Determination and Control System Testing Suite

Alexander R. Ghosh, **Patrick G. Haddox**, **Erik I. Kroeker** and
Victoria L. Coverstone, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.

This paper discusses the development of a magnetic-based attitude determination and control system for the IlliniSat-2, and the ground support equipment needed to validate the system. The IlliniSat-2 attitude determination is performed using magnetometers and coarse sun sensors applying an extended Kalman filtering technique, while the attitude control is performed with magnetic torquers. To conduct the flight testing of this system, a Helmholtz cage was developed. Lessons learned while developing the system and the testing apparatus, as well as the method for calibration of the system and the next steps in its development are also presented. [View Full Paper]

AAS 13 – 366

Estimation of Spacecraft Angular Acceleration Using Linear Accelerometers

Vivek Nagabhushan, **Norman G. Fitz-Coy** and **Shawn C. Johnson**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.

Knowledge of spacecraft angular acceleration may benefit several methods used to estimate spacecraft dynamic parameters. As opposed to differentiation of angular velocity measurements which amplifies sensor noise, this paper presents a method to determine the angular acceleration using measurements of linear acceleration at pre-determined points in the spacecraft. Multiple linear accelerometers are selectively situated in spacecraft for obtaining these measurements. Two such accelerometer configurations, using uniaxial, and triaxial accelerometers, respectively are presented. The effect of sensor bias, and noise on the angular acceleration estimates in both the cases are discussed and compared. The effective bias in the angular acceleration estimate is identified using a Kalman filter, and angular velocity measurements from a gyroscope. In addition to identifying the bias, the filter also produces smoothed angular velocity estimates. Simulations are performed using data from commercially available sensors.
[View Full Paper]

AAS 13 – 367

Closed-Form Optimal Maneuver Control Solutions for Under-Actuated Spacecraft

Donghoon Kim and **James D. Turner**, Aerospace Engineering Department, Texas A&M University, College Station, Texas, U.S.A.

In general, spacecraft are designed to be maneuvered to achieve pointing objectives. This is accomplished by designing a three-axis control system that can achieve arbitrary maneuvers, where the objective is to reorient the spacecraft and suppress the residual angular velocity at the end of the maneuver. If one of the three-axis control actuators fails, then new control laws are required. This paper explores optimal sequential Euler angle rotation strategies when only two control torque inputs are available. A key development is concerned with identifying maneuver switch-times for transitioning the control inputs among the remaining control devices. Many constraints are required for defining the optimal solution, which make the solution very sensitive to approximation errors for the switch-times that can require 40+ iterations to converge. A careful reformulation of the problem's necessary conditions in terms of two switch-times yields a closed-form solution that has been validated by nonlinear optimization experiments. Numerical applications demonstrate that the computational cost for solving the nonlinear optimal control maneuver problem is reduced by a factor of a minimum of $\sim 2.2 \times 10^6$-fold, which results from replacing the multiple shooting method optimization algorithm with the closed-form solutions obtained for the switch-times. A three-dimensional maneuver is presented to demonstrate the effectiveness of the proposed approach, and to compare the accuracy of the numerical and analytical solutions. [View Full Paper]

AAS 13 – 368

Attitude Tracking and Trajectory Planning for Underactuated Spacecraft

Dongxia Wang, **Yinghong Jia**, **Lei Jin** and **Shijie Xu**, School of Astronautics, Beihang University, Haidian District, Beijing, P.R. China

This paper provides some new results for the problem of attitude tracking control and on-line feasible trajectory generation for a symmetric rigid spacecraft with two controls. First, we deduce the attitude tracking models, and design the tracking control law based on the backstepping method. Second, we derive the necessary and sufficient condition of feasible trajectory according to the models characteristics, and utilize the notion of differential flatness to propose a simple way for designing the trajectory in the flat output space. Third, the control law and the feasible trajectory are simulated according to the different attitude tracking task. Both the theoretical and numerical results illustrate the validity of the control strategy in this paper. [View Full Paper]

AAS 13 – 369

Attitude Optimization of a Spinning Solar Sail Via Spin-Rate Control to Accelerate in Tangential Direction

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The spin axis direction of a spinning solar sail rotates around an equilibrium point near the Sun direction due to the influence of solar radiation pressure. This characteristic may lead to a complexity in the attitude control of the spacecraft. The objective of this research is to derive an optimal spin-rate control law for a spinning solar sail to maximize the solar radiation pressure acceleration in the tangential direction of its orbit. An analytical solution of a bang-bang control of the spin rate is derived using the calculus of variations, and its validity is verified with a numerical analysis. The control law determined in this study enables a spinning solar sail to accelerate continuously and explore the solar system. [View Full Paper]

AAS 13 – 370

Attitude Stabilization of a Spacecraft Underactuated By Two Parallel Control Moment Gyros

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Three-axis attitude stabilization of a spacecraft using only two control moment gyros (CMGs) mounted in parallel is addressed. The whole system is assumed to own zero angular momentum, which guarantees that the equilibrium attitude can be any orientation. However, the control objective involves a conflict that all singularities should be escaped to produce accurate torques while zero-momentum condition demands that an internal singularity, where the angular momentum vectors of two CMGs become antiparallel, must be approached for precise attitude stabilization. To solve this problem, a two-stage control strategy is developed. First, a novel saturated singular quaternion controller, which yields not only asymptotic convergence of the attitude trajectories but also bounded inputs, and a modified direct-inverse steering logic, which adds different magnitudes of error torques to escape internal and external singularities, are proposed to stabilize the attitude trajectories to a desired neighborhood of the equilibrium. Afterwards, a steady-state controller, using only one control torque as input, is derived to further minimize but not to precisely null the attitude error. The proposed method renders ultimately bounded attitude error and reveals a tradeoff between the two aforementioned incompatible requirements. Numerical simulation results validate the effectiveness of the proposed control algorithm. [View Full Paper]

AAS 13 – 321

High-Fidelity Geopotential Interpolation: Application to the Grace GGM03C Gravity Model

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With a goal of efficiently trading higher memory footprints for faster runtimes, a high fidelity interpolation method is presented for approximating a scalar quantity and associated gradients in the global 3D domain external to a sphere. The new "Fetch" interpolation model utilizes the weighting function method originally proposed by Junkins et al. to achieve continuity and smoothness. An overlapping grid strategy ensures a singularity-free domain, while minimizing associated memory costs. Local interpolating functions are judiciously chosen with a new adaptive, order-based selection of local polynomials which minimizes coefficient storage subject to a radially mapped residual tolerance. Analytic inversions of the normal equations associated with each candidate polynomial allow for rapid solutions to the least squares process without resorting to the conventional numerical linear system solvers. The gradient and higher order partial derivatives are computed directly with no memory cost, and are smooth and continuous to a user-specified order. The method is specifically applied to interpolate the Grace Gravity Model GGM03C geopotential up to degree and order 360. Highly tuned interpolation models of various resolutions are presented and discussed in detail. Released Fetch interpolation models of the geopotential include resolutions of 33x33, 70x70, 156x156, 360x360. The memory requirements span from 120 MB to 2360 MB, and the expected speedups over spherical harmonics evaluations span from ~10 to ~3000 fold. The break even resolution for runtime speeds is approximately degree and order 8. The models are globally continuous to order 3 and thus may be of interest to a variety of science and engineering applications. The runtime evaluation codes along with model coefficients are available on the internet. [View Full Paper]

AAS 13 – 371

Numerical Analysis of Thermal Radiation Perturbations for a Mercury Orbiter

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The perturbations induced by solar and thermal radiation are among the major design drivers for the mission design and operation of near-solar space missions. While the magnitude of these perturbations is proportional to the inverse square of the distance to the sun, their effects may vary drastically depending on the orbit and eclipse conditions. Furthermore, the spacecraft configuration, the optical properties as well as the attitude significantly affect the resulting magnitude and direction of the perturbations. Therefore, all of these effects need to be included in a high-fidelity analysis. While analytical methods offer a useful quick first-order assessment of the characteristics of the thermal effects, high-precision predictions can only be achieved by using numerical methods. They are able to incorporate any complicated spacecraft configuration as well as sophisticated environmental properties like, for instance, the thermo-optical properties of a planetary surface. Motivated by this, a numerical approach for the precise modelling of the solar and thermal effects acting on a Mercury Orbiter is presented. The expected disturbances resulting from thermal and solar perturbations are calculated for a Messenger-like mission. Due to the close distance to the sun and the high temperature gradients on the surface of Mercury, the evolving disturbances significantly affect the trajectory of the spacecraft. [View Full Paper]

AAS 13 – 372

Novel Orbits of Mercury and Venus Enabled Using Low-Thrust Propulsion

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Exploration of the inner planets of the Solar System is vital to significantly enhance the understanding of the formulation of Earth and other planets. This paper therefore considers the development of novel orbits of both Mercury and Venus to enhance the opportunities for remote sensing. Continuous low-thrust propulsion is used to extend the critical inclination of highly elliptical orbits at each planet, which are shown to require very small acceleration magnitudes. Unlike other bodies in the Solar System, natural sun-synchronous orbits do not exist at Mercury or Venus. This research therefore also uses continuous acceleration to enable both circular and elliptical sun-synchronous orbits, which could significantly simplify the spacecraft thermal environment. Considerably high thrust levels are however required to enable these orbits, which could not be provided by current propulsion systems. [View Full Paper]

AAS 13 – 373

Earth Orientation Parameter and Space Weather Data for Flight Operations

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Earth Orientation Parameter and Space Weather data are critical data elements for numerical propagation and space operations. Since CSSI first began assembling consolidated files of EOP and space weather data, we have tracked the performance of these data to better understand what operational users can expect. We present detailed analysis and results over the last few years to assess the best sources for this data, and recommend options for processing when no data exists. Corrections to space weather data are shown where anomalies exist. Finally, we investigate the implications of space weather prediction accuracy and its effect on satellite lifetime. [View Full Paper]

AAS 13 – 374

Refining Space Object Radiation Pressure Modeling With Bidirectional Reflectance Distribution Functions

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High fidelity orbit propagation requires detailed knowledge of the solar radiation pressure (SRP) on a space object. The SRP depends not only on the space object's shape and attitude, but also on the absorption and reflectance properties of each surface on the object. These properties are typically modeled in a simplistic fashion, but are here described by a surface bidirectional reflectance distribution function (BRDF). Several analytic BRDF models exist, and are typically complicated functions of illumination angle and material properties represented by parameters within the model. In general, the resulting calculation of the SRP would require a time consuming numerical integration. This might be impractical if multiple SRP calculations are required for a variety of material properties in real time, for example, in a filter where the particular surface parameters are being estimated. This paper develops a method to make accurate and precise SRP calculations quickly for some commonly used analytic BRDFs. Additionally, other non-gravitational radiation pressures exist including Earth albedo/Earth infrared radiation pressure, and thermal radiation pressure from the space object itself and are influenced by the specific BRDF. A description of these various radiation pressures and a comparison of the magnitude of the resulting accelerations at various orbital heights and the degree to which they affect the space object's orbit are also presented. Significantly, this study suggests that for space debris whose interactions with electro-magnetic radiation are described accurately with a BRDF, then hitherto unknown torques would account for rotational characteristics affecting both tracking signatures and the ability to predict the orbital evolution of the objects. [View Full Paper]

AAS 13 – 375

Essential Thrust Fourier Coefficient Set of Averaged Gauss Equations for Orbital Mechanics

Hyun Chul Ko and **Daniel J. Scheeres**, Department of Aerospace Engineering, University of Colorado at Boulder, Colorado, U.S.A.

By applying an averaging method to the Gauss equations, the perturbing accelerations acting on a satellite can be represented as a function of 14 constant Thrust Fourier Coefficients (TFCs). Time rate changes of mean orbital element (OE)s related to these TFCs are analyzed and the representation of these thrust coefficients as a function of change in orbit states is studied. Selected minimum sets of 6 TFCs are able to provide a finite basis representation of arbitrary orbital maneuvers that allow us to dynamically interpolate between states across an unknown maneuver. Using the essential TFC set, different types of solutions are obtained and a comparison study of these solutions is also conducted. [View Full Paper]

AAS 13 – 376

An Algorithm for Trajectory Propagation and Uncertainty Mapping on GPU

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

This paper introduces an efficient parallel numerical integrator for use on graphics processing units (GPUs) to propagate large sets of trajectories. The method is based on modifying Picard iterations to fit the structure of GPUs. This enables the efficient computation of orbital properties on sections of initial conditions of a dynamical system. This is applied to the problem of state uncertainty propagation, where the use of an unscented transformation further allows to optimize the grid of initial conditions to propagate. Thereby, it reduces the overall computational load for such problems.
[View Full Paper]

AAS 13 – 377

Trajectory Evolution Under Laser Photonic Propulsion in the Two-Body Problem

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The photonic laser propulsion (PLP) system can produce continuous and constant thrust. This paper reviews its basics and then studies its application in the two-body interplanetary trajectory. This study also derives the equations of motion (EOM) for a spacecraft in an inertial frame for the two-body problem, and variation of orbit elements. This study introduces the Gauss' Equations to evaluate the evolution of orbit elements, and normalizes the Gauss' Equations with parameters of mother ship. The evolution of orbit elements also confirms the constraint on the smallest thrust at the launching stage. Numerical simulations are provided in this paper. The results of this paper are directly applicable to future PLP thrust missions, and particularly interplanetary travel.
[View Full Paper]

AAS 13 – 378

A Semi-Analytical Approach to Study Resonances Effects on the Orbital Motion of Artificial Satellites

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A semi-analytical approach is proposed to study resonances effects on the orbital motion of artificial satellites or space debris orbiting the Earth. Applying successive Mathieu transformations, the order of dynamical system is reduced and the final system is solved by numerical integration. In the simplified dynamical model, we can choose the resonance to be considered as critical angle. Simulations are presented showing the variations of the orbital elements of bodies orbiting in the neighbourhood of the 2:1, 14:1 and 15:1 resonance condition. The half-width of the separatrix is calculated through a linearized model which describes the behavior of the dynamical system in a neighborhood of each critical angle. [View Full Paper]

AAS 13 – 379
(Paper Withdrawn)

AAS 13 – 380
(Paper Withdrawn)

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(Paper Withdrawn)

AAS 13 – 491

Accurate and Fast Orbit Propagation With a New Complete Set of Elements

Giulio Baù, Department of Mathematics, University of Pisa, Celestial Mechanics Group, Pisa, Italy; **Claudio Bombardelli** and **Jesús Peláez**, E.T.S.I. Aeronáuticos, Universidad Politécnica de Madrid, Space Dynamics Group, Madrid, Spain

A formulation of the perturbed two-body problem that relies on a new set of seven orbital elements and a time-element is presented. The proposed method generalizes the special perturbation method published by Peláez et al. in 2007 for the case of a perturbing force that is partially or totally derivable from a potential. We accomplish this result by employing a generalized Sundman time transformation in the framework of the projective decomposition, which is a known approach for transforming the two-body problem into harmonic oscillators. In order to reduce the numerical error produced by the time transformation an element with respect to the physical time is defined and implemented as a dependent variable in place of the physical time itself. Numerical tests, carried out with examples extensively used in the literature, show the remarkable improvement of the performance of the new set of elements for different kinds of perturbations and eccentricities. Moreover, the method reveals to be competitive and even better than two very popular element methods derived from the Kustaanheimo-Stiefel and Sperling-Burdet regularizations. [View Full Paper]

SESSION 20: INTERPLANETARY MISSION STUDIES

Chair: Dr. Jon Sims, Jet Propulsion Laboratory

AAS 13 – 382

MESSENGER's Maneuvers to Reduce Orbital Period During the Extended Mission: Ensuring Maximum Use of the Bi-Propellant Propulsion System

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Two orbit-correction maneuvers (OCMs) were required during MESSENGER's extended mission to reduce the orbital period from 11.6 to 8 hours. The OCMs were designed as a pair to maximize use of the bi-propellant propulsion system. The first maneuver was designed to be flexible to a range of values for the amount of oxidizer remaining in the system. A special autonomy scheme was necessary to respond to oxidizer depletion and continue the maneuver without interruption using only monopropellant thrusters. The second maneuver executed four days later and was designed on the basis of the performance of the first maneuver. [View Full Paper]

AAS 13 – 383

MESSENGER Navigation Operations During the Mercury Orbital Mission Phase

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The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is the seventh in NASA's Discovery Program. The spacecraft was launched from Cape Canaveral Air Force Station in August 2004 to begin an interplanetary cruise that culminated in orbit insertion about Mercury in March 2011 for a nominal one-year scientific investigation. An extension to the mission was initiated in March 2012, and in order to optimize the scope and return of the onboard scientific instruments and the stability of the spacecraft orbit about the planet, the orbital period was reduced from 12 to 8 hours in April 2012. This paper describes MESSENGER navigation operations and trajectory estimation performance for the orbital mission phase from Mercury orbit insertion through the end of the primary mission and into the first 9 months of the ongoing extended mission. [View Full Paper]

AAS 13 – 384

Transfer Trajectory Design for the Mars Atmosphere and Volatile Evolution (MAVEN) Mission

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The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission will determine the history of the loss of volatiles from the Martian atmosphere from a highly inclined elliptical orbit. MAVEN will launch from Cape Canaveral Air Force Station on an Atlas-V 401 during an extended 36-day launch period opening November 18, 2013. The MAVEN Navigation and Mission Design team performed a Monte Carlo analysis of the Type-II transfer to characterize; dispersions of the arrival B-Plane, trajectory correction maneuvers (TCMs), and the probability of Mars impact. This paper presents detailed analysis of critical MOI event coverage, maneuver constraints, ΔV-99 budgets, and Planetary Protection requirements. [View Full Paper]

AAS 13 – 385

Hybrid Propulsion Transfers for Mars Science Missions

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F. Topputo and **M. Massari**, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Italy

Special Earth-Mars transfers that exploit both chemical and solar electric propulsion are investigated in this work. A dedicated launch strategy via Soyuz is considered. Firstly, a high-thrust, low-Isp impulse is used to place the spacecraft onto an Earth-escape trajectory, possibly performing a lunar swingby. Then, an heliocentric rendezvous with Mars is achieved via low-thrust, high-Isp propulsion, followed by a ballistic capture leading to a final, low-altitude orbit around Mars. Hybrid propulsion transfers outperform chemical transfers (Hohmann) in terms of propellant consumption. Furthermore, a few considerations at system level are also proposed. [View Full Paper]

AAS 13 – 386

An Orbit Design of Akatsuki to Avoid Long Eclipse on its Orbit Around Venus

Yasuhiro Kawakatsu, ISAS/JAXA, Sagamihara, Kanagawa, Japan

AKATSUKI, the Japanese Venus explorer, once failed to inject itself into an orbit around Venus in 2010. AKATSUKI is now on its way to re-encounter Venus in 2015. However, due to a malfunction in the propulsion system, AKATSUKI can be only injected into the orbit much higher than that originally planned. It causes a couple of issues to be considered in its orbit design around Venus. One of which is long eclipse, which is the main topic of this paper. This paper introduces an orbit design strategy to avoid the long eclipse. An example of design result is shown as well. [View Full Paper]

AAS 13 – 387

Observations Planning Optimization for Bepicolombo's Mercury Rotation Experiment

Alessandra Palli and **P. Tortora**, Dipartimento di Ingegneria Industriale, Università di Bologna, Forlì (FC), Italy; **Rachele Meriggiola** and **Luciano Iess**, Dipartimento di Ingegneria Meccanica e Aerospaziale, Università di Roma "Sapienza", Rome, Italy

The achievement of the desired accuracies in estimating Mercury's rotational parameters in the frame of the radio science experiment hosted on board ESA's BepiColombo mission strongly depends upon a scrupulous analysis of the most suitable observations.

In this case, observables are constituted by images captured by the High Resolution Imaging Channel (HRIC) depicting the same portion of the surface at two different epochs which, opportunely georeferenced and transposed in an inertial reference frame, provide information on the displacement of the features identified in the images and thus on the rotation of the planet.

The critical part in the accomplishment of the experiment is represented by the fact that observations will be limited by mission constraints and therefore selection criteria need to be applied to filter the database and choose the ones characterized by the highest information content. Hence, screening parameters could be illumination conditions or altitude variations between images to be compared in order to favor their matching, rather than a temporal gap allowing to observe a consistent change in libration.

All these aspects are encompassed in a global simulator of the experiment, deemed to be the most effective way to analyze the problem. The final aim of the software is to converge toward a solution ensuring the maximum scientific output with the minimum number of observations. In order to do so, the simulator first generates a database of the spacecraft ground tracks, selects the dataset of observations and implements an optimization algorithm. In parallel to the analyses performed using the optimizator, other independent simulations have been run so as to investigate on the minimum number of observations needed to obtain the desired accuracies. Hence, while the last ones provides an hint on the quantity of measurements needed, the end-to-end simulator is aimed at individuating the most favorable strategy of observation, in terms of epochs and surface features. [View Full Paper]

AAS 13 – 388

The Trajectory Control Strategies of Akatsuki for Venus Orbit Reinsertion

Chikako Hirose, **Nobuaki Ishii** and **Yasuhiro Kawakatsu**, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Chiaki Ukai** and **Hiroshi Terada**, NEC Aerospace Systems, Ltd., Fuchu-shi, Tokyo, Japan

The Japanese Venus explorer "Akatsuki (PLANET-C)", which now rotates about the Sun, will approach to Venus again in 2015. For the Venus orbit reinsertion, several trajectory strategies were devised. In this paper, we introduce the difficulties we faced in redesigning the trajectory of Akatsuki after the failure of the first Venus Orbit Insertion (VOI) in 2010 and report some newly devised trajectory control strategies including Gravity Brake Method, which will make the most of the solar perturbations to conduct the Venus orbit insertion for the second time. [View Full Paper]

AAS 13 – 494

Jovian Tour Design for Orbiter and Lander Missions to Europa

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Europa is one of the most interesting targets for solar system exploration, as its ocean of liquid water could harbor life. Following the recommendation of the Planetary Decadal Survey, NASA commissioned a study for a flyby mission, an orbiter mission, and a lander mission. This paper presents the moon tours for the lander and orbiter concepts. The total Δv and radiation dose would be reduced by exploiting multi-body dynamics and avoiding phasing loops in the Ganymede-to-Europa transfer. Tour 11-O3, 12-L1 and 12-L4 are presented in details and their performances compared to other tours from previous Europa mission studies. [View Full Paper]

SESSION 21: RENDEZVOUS AND FORMATION FLYING
Chair: Dr. Ossama Abdelkhalik, Michigan Technological University

AAS 13 – 389

Optimal Formation Keeping Near a General Keplerian Orbit Under Nonlinear Perturbations

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This study presents a semi-analytic approach for optimal spacecraft formation keeping with high precision. For a continuous-thrust propulsion system, a nonlinear optimal tracking law is derived in generic form as an explicit function of the states by employing generating functions in the theory of Hamiltonian systems. Optimal formation keeping problems are formulated with respect to a time-varying reference trajectory on a finite time span to accommodate nonlinearities more precisely. The applicability of the overall process is not affected by the complexity of dynamics and the selection of coordinates. As it allows us to design a nonlinear optimal feedback control in the Earth-centered inertial frame, a variety of nonlinear perturbations can be incorporated without complicated coordinate transformations. Numerical experiments demonstrate that the nonlinear tracking control logic results in superior tracking accuracy and cost reduction by accommodating higher-order nonlinearities. [View Full Paper]

AAS 13 – 390

Orbit Trajectory Design for the Boeing Commercial Crew Transportation System

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Under a Space Act Agreement with the NASA Commercial Crew Office, Boeing is pursuing design, development, and operation of a transportation system that delivers crew and cargo to the International Space Station (ISS) and future Bigelow Space Complex (BSC). The launch vehicle and Boeing spacecraft will be capable of both automated (no human interaction) and autonomous (no ground assistance) flight from lift-off to docking and undocking to landing. For safety and mission assurance purposes, a pilot will oversee the onboard system and can break out of ascent, rendezvous, deorbit, and landing automation; to manually dock or return the vehicle and crew safely to earth. Orbit and entry trajectory design is derived from techniques proven on Apollo-Skylab, Space Shuttle, and Orbital Express missions; mixed with new algorithms Boeing developed internally and for other programs. This paper describes design of the CST-100 mission with emphasis on orbit trajectories and automation while in free-flight. This includes the flight path and attitudes chosen for rendezvous and docking – using both vehicle automation and manual piloting techniques. The paper discusses execution of the trajectories by GNC and onboard flight management, along with limits and challenges encountered along the way. [View Full Paper]

AAS 13 – 391

Minimum Time Rendezvous Using Differential Drag

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This paper presents a method to solve the minimum time rendezvous problem of two spacecraft using differential drag. The control set is losslessly relaxed so that the problem can be converted from a mixed integer nonlinear programming problem, to a nonlinear programming problem, and finally to a sequence of linear programming problems with guaranteed convergence to the global minimum in polynomial time. Compared to solving the nonlinear programming problem, the computation time is reduced from about 1.5 seconds to 0.03 seconds. Compared to an analytical, sub-optimal solution, the flight time is reduced from 5.47 hours to 4.09 hours. In light of the convergence properties and efficient linear program solvers, the method is well suited for onboard, real-time use. [View Full Paper]

AAS 13 – 392

Optimal Maintenance of Relative Circular Inertial Motion for Nulling Interferometry Applications

Stefano Casotto and **Nicola Baresi**, Department of Physics and Astronomy, University of Padua, Italy

Spacecraft Formation Flying (FF) is a modern technology in Space Mission Design. Many recent missions have been designed based on this new architecture, in which a number of small, cost-effective satellites cooperate in space in order to achieve certain mission objectives. However, to ensure the feasibility of this paradigm, engineers have to deal with plenty of issues such as the necessity to maintain the formation geometry in a perturbed environment. A solution to this problem is given by optimal control theory, which allows to find the acceleration profile required to reach and keep the desired configuration in the most efficient way (e.g., by minimizing fuel consumption). Accordingly, a Linear Quadratic Tracker (LQT) and a Linear Quadratic Regulator (LQR) has been developed to study the formation keeping of two satellites in a J2-perturbed elliptic orbit. Despite a majority of investigations relies on the inaccurate Hill-Clohessy-Wiltshire model of relative motion, it will be shown that a more realistic dynamical model of the system dynamics leads to appreciable fuel savings. As a test case, a two-satellite configuration has been selected in which one spacecraft—the follower—orbits around the other—the leader—in a plane perpendicular to the line of sight to a chosen star, e.g. αCen, following a circular path covered in a given period. This is akin to the case of nulling interferometry on an Earth-bound orbit, an analogue motion that has been used in the simulations. This model is derived in the Earth Centered Inertial frame (ECI) and is valid for any eccentric orbit. Furthermore, of the back-up configuration of the L2-positioned Darwin mission. Here we study one of the several spokes or one collector-combiner pair of the full mission configuration. In particular, we first illustrate a Numerical Model (NM) of the relative it takes into account the second zonal harmonic of the Earth's gravitational field. Second, the optimal control profile for maintaining the configuration is found by solving the Differential Riccati Equation (DRE) either with the LQT or the LQR. Once the best control scheme is determined and the accelerations found, the ΔV required per orbit can be estimated and different configurations can be compared. Accordingly, the most efficient formations to satisfy the nulling interferometry requirements for satellites in Earth orbit can be determined. For example, we have investigated the difference in fuel consumption by varying the eccentricity and semimajor axis of the leader spacecraft. In addition, a parametric survey has been performed to quantify the effects of the target choice and the inclination of the leader's orbit on the total formation keeping cost. That is, the ΔV required per orbit has been calculated as a function of right ascension and declination of the target and for six different inclination values. [View Full Paper]

AAS 13 – 393

Application of Relative Satellite Motion Dynamics to Lambert's Problem

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In this paper, the well-known Lambert problem, which has no known closed-form solution for inertial dynamics, is investigated as a rendezvous problem, whereby a deputy is to rendezvous with a fictitious chief. Solutions to the problem are presented using a method based on the Hill-Clohessy-Wiltshire model, a well-known linear solution for relative motion, as well as a method based on a recently derived closed-form relative motion solution with second-order fidelity. The accuracy of both guidance schemes is then compared to the "true" two-body solution for various orbital scenarios.
[View Full Paper]

AAS 13 – 394
(Paper Withdrawn)

AAS 13 – 395

Impulsive Hovering Formation Based on Relative Orbit Elements

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A new set of relative orbit elements (ROE) is defined to describe the geometric characteristics of the hovering formation. An impulsive feedback control strategy based on ROE is proposed to put a satellite into a hovering pattern relative to the reference satellite. The formation can be controlled from any configuration to the hovering formaion using the proposed control method. The error correction of the control laws is de - veloped. The impulsive fuel cost of the non-Keplerian relative motion is studied compared to the continuous thrust control method. Several numerical simulations are presented to demonstrate the proposed hovering formation model. [View Full Paper]

AAS 13 – 396

Lyapunov-Based Guidance Schemes for In-Plane Rendezvous Using Levi-Civita Coordinates

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We present closed-loop guidance schemes using Lyapunov stability theory for rendezvous. Our model adopts the Levi-Civita transformation of the planar two-body problem. The advantage of working in these coordinates is that the solution to the unperturbed equations of motion is that of a linear harmonic oscillator, so the analytical solution is explicitly characterized during any coast phase. The control scheme progresses through thrust-coast regimes covering two main phases: first, a matching of the target's semi-major axis, and second, a matching of position and velocity of the target, to achieve rendezvous. No restrictions are posed upon the initial position and velocity separations between the chaser and target. The control algorithm is robust, computationally fast, and can be used for both low- and high-thrust problems. [View Full Paper]

AAS 13 – 397

Formation Flying Near the Libration Points by Impulse Control

Mai Bando, Department of Aeronautics and Astronautics, Kyushu University, Nishu-ku, Fukuoka, Japan; **Akira Ichikawa**, Department of System Design and Engineering, Nanzan University, Seto, Aichi, Japan

Formation flying along a halo orbit near the L_1 point in the Sun-Earth circular restricted three-body system with impulse control is considered. The reference orbit is a periodic perturbation of the halo orbit generated by an exosystem, and the output regulation theory for discrete system is employed for the transition and maintenance. The minimum impulse number and the total velocity change required for the maintenance of the halo orbit are shown. Then the total velocity change for the maintenance of the perturbed reference orbits is shown. Finally, formation flying near the L_1 point is considered, where the reference orbit is a periodic orbit whose frequency is equal to that of the linearized equations of motion at the L_1 point. [View Full Paper]

AAS 13 – 474

Study of Elliptical Relative Motion Control Based on Relative Orbit Elements

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A new impulsive feedback control law is developed for the elliptical relative motion based on relative orbit elements (ROE). The control of the in-plane and out-of-plane relative motions can be completely decoupled using the new method, which are suitable for both elliptical and circular reference orbits. The ROE-based control method needs four thrusts to achieve the elliptical relative motion control. Two different impulsive in-plane control methods are proposed. Different typical orbit maneuvers, including formation establishment, reconfiguration, long-distance maneuver and formation keeping are simulated to demonstrate the performance of the proposed ROE-based control laws. [View Full Paper]

SESSION 22:
FLIGHT DYNAMICS OPERATIONS AND SPACECRAFT AUTONOMY
Chair: David Dunham, KinetX, Inc.

AAS 13 – 398

Verification of the Orekit Java Implementation of the Draper Semi-Analytical Satellite Theory

Paul J. Cefola, Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Amherst, New York, U.S.A.; **Barry Bentley**, University of Cambridge, Cambridge, United Kingdom; **Luc Maisonobe**, **Pascal Parraud** and **Romain Di-Costanzo**, CS Communications & Systemes, Toulouse, France; **Zachary Folcik**, MIT Lincoln Laboratory, Lexington, Massachusetts, U.S.A.

Verification of the **java Orekit** implementation of the Draper Semi-analytical Satellite Theory (DSST) is discussed. The Orekit library for space flight dynamics has been published under the open-source **Apache license V2**. The DSST is unique among analytical and semi-analytical satellite theories due to the scope of the included force models. However, the DSST has not been readily accessible to the wider Astrodynamics research community. Implementation of the DSST in the Orekit library is a comprehensive task because it involves the migration of the DSST to the object-oriented **java language** and to a different **functional decomposition strategy**. The resolution of the code and documentation anomalies discovered during the verification process is the important product of this project. [View Full Paper]

AAS 13 – 399

Cubesat Collision Risk Analysis at Orbital Injection

Mauro Pontani, University of Rome "La Sapienza", Rome, Italy; **Chantal Cappelletti**, Group of Astrodynamics for the Use of Space Systems, s.r.l., Rome, Italy

The CubeSat project is aimed at increasing accessibility to space, due to the limited costs and development times for such nanosatellites. Usually CubeSats are released in clusters and, in the absence of any maneuver capability, collision risk analysis is necessary. Nanosatellites dynamics after release depends on (i) the release conditions and (ii) orbital relative motion. The most common release modality consists of delivering three CubeSats at a time, using a customized dispenser. Orbital relative motion can be described through the linearized Clohessy-Hill-Wiltshire equations or through more refined dynamical models. This research includes a worst-case analysis, with reference to two distinct operational orbits, after formulating the problem as a parameter optimization problem, where the unknown parameters are the CubeSats relative velocity vectors at release. The swarming methodology is employed as numerical solving technique, and leads to establishing the delivery conditions for which collisions can occur. In these cases, the effect of two successive CubSats releases, with a sufficient delay between each other, is proven to mitigate the collision risk. [View Full Paper]

AAS 13 – 400

Effects of the Local Plasma Environment on the Dynamics of Electrodynamic Tether Systems

John A. Janeski, Department of Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.; **Christopher D. Hall**, Department of Mechanical Engineering, University of New Mexico, Albuquerque, New Mexico, U.S.A.; **Wayne A. Scales**, Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

An electrodynamic tether (EDT) system consists of two satellites connected by a long tether that generates current to produce either power or thrust via the system's electromagnetic interaction with the space environment. A complete system model for an EDT is developed that combines a high-fidelity tether dynamics model and a model for the tether current governed by local plasma properties. Variations in the tether system dynamics due to the tether current are investigated and compared to experimental data from the Plasma Motor Generator mission. The International Reference Ionosphere model generates the plasma parameters for the current collection model.
[View Full Paper]

AAS 13 – 401

Planning and Execution of a Specialized Maneuver for the ARTEMIS Mission: Achieving Three Goals With One Sequence

Jeffrey E. Marchese, **Daniel Cosgrove**, **Sabine Frey** and **Manfred Bester**, Space Sciences Laboratory, University of California, Berkeley, California, U.S.A.

After lunar orbit insertion (LOI) the ARTEMIS probes, designated P1 and P2, were in sub-optimal states with regard to attitude and spin-rate. We describe herein our project to design and apply a maneuver sequence performed on P2 to simultaneously alter the spin-rate, the attitude and apsides. The implementation of the maneuver sequence resulted in the correction of the requisite parameters with significant fuel savings over executing equivalent single-purposed maneuvers. [View Full Paper]

AAS 13 – 402
(Paper Withdrawn)

AAS 13 – 403
(Paper Withdrawn)

AAS 13 – 404
(Paper Withdrawn)

AAS 13 – 405
(Paper Withdrawn)

AAS 13 – 406

Long-Term Attitude and Orbit Prediction of Solar Sailing IKAROS While Being Lost in Space

Yuya Mimasu, **Yoji Shirasawa**, **Katsuhide Yonekura**, **Osamu Mori**, **Ryu Funase**, **Takanao Saiki** and **Yuichi Tsuda**, JAXA Space Exploration Center (JSPEC), Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Sho Taniguchi**, Technical Computing Solutions Unit, Science Solutions Division, Fujitsu Limited, Shiodome City Center, Higashi-Shimbashi, Minagto-ku, Tokyo, Japan;
Hiroshi Takeuchi, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

The world's first solar sail IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) which is operated by Japan Aerospace Exploration Agency (JAXA) lost communication with the ground station due to the power shortage on December 24, 2011. In order to acquire IKAROS again after the power comes back, we immediately initiated to predict the attitude and orbit for the spacecraft. As the result of the effort for the prediction, finally we acquire IKAROS after 9 months. This paper presents that the attitude and orbit prediction technique, while IKAROS was lost in space.
[View Full Paper]

AAS 13 – 407

In-Flight Aerodynamic and Mass Properties Identification Design for Mars Aerobraking

Ling Jiang and **Shijie Xu**, Department of Aerospace Engineering, School of Astronautics, Beihang University, Beijing, China; **Chunling Wei**, Science and Technology on Space Intelligent Control Laboratory, Beijing Institute of Control Engineering, Beijing, China

Aerobraking is a revolutionary technique that has been used successfully in recent Mars missions. But consideration of significant risk and cost has led to the development of autonomous aerobraking design. This paper proposes a novel method of estimating varying aerodynamic and mass properties in-flight to improve the onboard capacity for corridor controller design. The identification approach is divided into two steps: executing mass properties identification at the apoapsis walk-in and adjustment maneuvers first, and then implementing aerodynamic property estimation during atmospheric passes. Simulation results show that the proposed approach is simple and effective, making it suitable for on-board real-time computation. [View Full Paper]

AAS 13 – 443

Optical Navigation Capabilities for Deep Space Missions

Coralie D. Jackman and **Philip J. Dumont**, Space Navigation and Flight Dynamics Practice, KinetX, Inc., Simi Valley, California, U.S.A.

KinetX Aerospace, a private corporation, is currently providing navigation for three NASA deep space missions: MESSENGER, New Horizons, and OSIRISREx. Two of these, New Horizons to the Pluto system, and OSIRIS-REx to the asteroid 1999 RQ36, rely heavily on optical navigation (OpNav) to ensure mission success. KinetX-developed OpNav software uses spacecraft imaging to determine the spacecraft trajectory and targets' ephemerides. This paper describes the KinetX approach to optical navigation, simulating spacecraft images for testing, processing real data, and generating products for orbit determination. Also included are imaging simulations for New Horizons and OSIRIS-REx and real data results from New Horizons. [View Full Paper]

AAS 13 – 498

A Scheme for Simplified Trajectory Design in Aero-Gravity Assist Using Singular Orbits

Naoko Ogawa, JAXA Space Exploration Center, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Kazuhisa Fujita**, Aerospace Research and Development Directorate, JAXA, Chofu, Tokyo, Japan; **Jun'ichiro Kawaguchi**, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

This paper proposes a novel strategy for simplified trajectory design in aero-gravity assist missions. In aero-gravity assists, the extent of deceleration and the periapsis altitude are coupled and dependent to each other, which makes it difficult to obtain desired outgoing trajectory. We insert a one-revolution orbit as a trajectory leg just after the aero-gravity assist so that we can utilize degrees of freedom in design for connecting two trajectory before and after the swing-by. After one-revolution interplanetary cruise, the S/C re-encounters the planet and thus has a chance to go to new destination by a usual gravity assist, or to experience aero-gravity assist again, which allows us various interplanetary missions afterward. This paper describes the difficulty in design of aero-gravity assists, outline of our novel approach and its detailed procedures. A case study for Earth aero-gravity assist design is also shown. [View Full Paper]

SESSION 23: SMALL-BODY MISSIONS
Chair: Dr. Ryan Park, Jet Propulsion Laboratory

AAS 13 – 408

Classification of Distant Earth-Return Trajectories for Near-Earth Asteroid Mission Applications

Nicholas Bradley 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.

A classification is presented that categorizes free-return trajectories in the Earth-Sun rotating frame that begin and end near the Earth with no intermediate velocity adjustments. Candidate trajectories and trajectory families are searched to determine possible orbits to rendezvous with near-Earth asteroids. Determination of trajectory families is accomplished via a numerical search technique, which uses a constrained zero-cost optimization algorithm combined with a particle swarm algorithm. Hundreds of candidate trajectories are found, satisfying constraints at Earth and escape energy conditions. The trajectories are classified in five different categories based on common characteristics in orbital plane, direction, and time of flight. Additionally, an example rendezvous orbit is shown involving near-Earth asteroid 2000 SG344 in the years 2027-2028. [View Full Paper]

AAS 13 – 409

Trajectories to Nab a NEA (Near-Earth Asteroid)

Damon Landau, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **John Dankanich**, NASA Programs, AeroDank, Inc., Cleveland, Ohio, U.S.A.; **Nathan Strange**, Mission Concepts Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **Julie Bellerose**, Carnegie Mellon University / NASA ARC, Moffett Field, California, U.S.A.; **Pedro Llanos**, Flight Mechanics Group, GMV, Madrid, Spain; **Marco Tantardini**, Visiting Fellow, The Planetary Society, Pasadena, California, U.S.A.

In 2010 and 2011 NASA and Keck Institute for Space Studies sponsored investigations into the feasibility of identifying, capturing, and returning an entire (albeit small) NEA to the vicinity of Earth, and concluded that a 40-kW solar electric propulsion system launched on an Atlas 551 provided sufficient propulsion to control an asteroid's trajectory. Once secured by the spacecraft, a NEA with a naturally close encounter with Earth is nudged over a few years to target a lunar gravity assist, capturing the object into Earth orbit. With further use of solar perturbations, up to 3,600,000 kg of NEA could be placed in high-lunar orbit. [View Full Paper]

AAS 13 – 410

(Paper Withdrawn)

AAS 13 – 411

Design, Dynamics and Stability of the OSIRIS-REx Sun-Terminator Orbits

D. J. Scheeres and **A. J. Rosengren**, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, The University of Colorado, Boulder, Colorado, U.S.A.; **B. M. Sutter**, Lockheed Martin Space Systems Company, Littleton, Colorado, U.S.A.

The orbital dynamics of close proximity motion about an asteroid in a solar radiation pressure (SRP) dominated environment is analyzed. A previously derived solution for the secular motion of an orbiter in this environment is restated and studied in detail for application to the orbital phase of NASA's OSIRIS-REx mission to asteroid 1999 RQ36. Using the secular solution we are able to carry out a nominal design of the orbit phase with constraints on the oscillations expected in the orbit elements and spacecraft orbit geometry. We also probe the limits of the secular solution, and show that low orbits are sufficiently perturbed by the asteroid gravity field to destabilize certain classes of orbits. The analytical averaged solutions are validated with numerical integrations and through implementation in Satellite ToolKit (STK). [View Full Paper]

AAS 13 – 412

Electric Propulsion Alternatives For The OSIRIS-REx Mission

Kamesh Sankaran, **Jonathan Hoff** and **Chris Grochowski**, Physics Department, Whitworth University, Spokane, Washington, U.S.A.

This study evaluated the ability of eight existing ion and Hall thrusters to meet some of the key requirements of the OSIRIS-REx mission – to carry a dry mass of at least 750 kg to the asteroid 1999RQ36, land on it in 2019, stay on the asteroid for an extended period, and return with a sample of the asteroid to Earth. The thrusters were chosen based on demonstrated performance and lifetime characteristics at power levels higher than 5 kW, and were evaluated for this mission at their measured performance levels. The thrusters were evaluated for various values of the specific mass of the power plant and different values of stay time on the asteroid. The resulting values of total trip time and wet mass at LEO for the evaluated thrusters, for varying values of stay time on the asteroid, are presented and are compared with the existing plan of 7-year round-trip plan of the OSIRIS-REx mission with an Atlas-V class launch vehicle.
[View Full Paper]

AAS 13 – 413

Terminal Guidance Navigation for an Asteroid Impactor Spacecraft

Shyam Bhaskaran and **Brian Kennedy**, Navigation and Mission Design Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Near Earth Asteroids could potentially cause a great deal of devastation if one were to impact the Earth. If such an asteroid were found, the next step would be to mitigate the threat by one of several options, the most viable of which is to deflect the asteroids trajectory such that it misses the Earth by hitting it at a very high velocity with a spacecraft. The technology to perform such a deflection has been demonstrated by the Deep Impact (DI) mission, which successfully collided with comet Tempel 1 in July 2005 using an onboard autonomous navigation system, called AutoNav, for the terminal phase of the mission. In this paper, we evaluate the ability of AutoNav to impact a wide range of scenarios that an deflection mission could encounter, varying parameters such as the approach velocity, phase angle, size of the asteroid, and the determination of spacecraft attitude. Using realistic Monte Carlo simulations, we tabulated the probability of success of the deflection as a function of these parameters, and find the highest sensitivity to be due the spacecraft attitude determination mode. We conclude with some recommendations for future work. [View Full Paper]

AAS 13 – 414

Trajectory Exploration Within Binary Systems Comprised of Small Irregular Bodies

Loic Chappaz and **Kathleen Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

In an initial investigation into the behavior of a spacecraft near a pair of irregular bodies, consider three bodies (one massless). Two massive bodies form the primary system that is comprised of an ellipsoidal primary (P_1) and a second spherical primary (P_2). Two primary configurations are addressed: 'synchronous' and 'non-synchronous'. Concepts and tools similar to those applied in the Circular Restricted Three-Body Problem (CR3BP) are exploited to construct periodic trajectories for a third body in synchronous systems. In non-synchronous systems, however, the search for third body periodic orbits is complicated by several factors. The mathematical model for the third-body motion is now time-variant, the motion of P_2 is not trivial and also requires the distinction between P_1- and P_2-fixed rotating frames. [View Full Paper]

AAS 13 – 415

Close Proximity Spacecraft Operations Using Stereoscopic Imaging

Jacob Darling, **Keith LeGrand**, **Henry J. Pernicka** and **Bharat Mahajan**; Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

The relative guidance, navigation, and control of a pair of spacecraft using real-time data from a stereoscopic imaging sensor are investigated. Because line-of-sight measurements from a single imager are typically insufficient for system observability, a second imager with a known baseline vector to the first imager is included to achieve system observability with the addition of relative range measurements. The stereoscopic imaging system as modeled provides measurements capable of achieving a complete navigation solution. An SDRE controller is used to provide closed-loop control to maintain a desired relative orbit. An Unscented Kalman Filter is used to estimate the chief spacecraft's inertial states using GPS measurements and the deputy spacecraft's inertial states with stereoscopic imaging relative position measurements. Relative Orbital Elements are implemented to model separation between the spacecraft. [View Full Paper]

AAS 13 – 416

Alternative Hybrid Propulsion Transfers for Marco Polo NEOs Sample Return Mission

Mauro Massari and **Francesco Topputo**, Department of Aerospace Science and Technology, Politecnico di Milano, Milano, Italy; **Giorgio Mingotti**, Advanced Space Concepts Laboratory, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, United Kingdom

In this paper the new concept of hybrid propulsion transfers is applied to the trajectory design for the ESA Marco Polo mission, a NEO sample return mission. The concept of hybrid propulsion transfers combine the features of low-energy transfer, which implies impulsive maneuver accomplished using chemical propulsion, and low-thrust transfer. The optimization is performed with a direct transcription procedure. The problem is formulated as a nonlinear programming problem and solved for a finite set of variables, maximizing the final spacecraft mass. The designed hybrid propulsion transfers have been in-depth compared with the baseline trajectories obtained for Marco Polo mission. [View Full Paper]

AAS 13 – 417

A Simulation Study of Gravity and Ephemeris Estimation of Asteroid 1999JU3 Using Spacecraft Radiometric Tracking, Optical, and Altimeter Measurements

Hitoshi Ikeda, Trajectory and Navigation Group, Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, Japan; **Yuichi Tsuda**, **Yuya Mimasu** and **Makoto Yoshikawa**, JAXA Space Exploration Center (JSPEC), Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

The Japanese asteroid explorer Hayabusa-2 will be launched in the mid-2010s to return samples from C-type near-Earth asteroid 1999JU3. During the rendezvous phase (i.e. proximity operation phase), we will conduct scientific observations to estimate physical parameters (e.g. gravity field, shape, pole direction, spin-rate, ephemeris) of the target body, which are crucial not only for its scientific investigation but also for spacecraft navigation. In particular, the mass is essential to perform a stable touchdown sequence to collect samples from the asteroids surface. We will attempt to estimate the gravity field of the target body using Earth-based radiometric tracking measurements (2-way Doppler and range) and spacecraft-based measurements (information from optical navigation cameras and laser altimeter) using a global parameter estimation technique. As the first step for gravity field estimation, we performed a simulation study on mass estimation under simple configuration and evaluated the relation between the quality and quantity of measurements and the accuracies of the estimation results. Subsequently, the detectability of the low degree and order gravity field coefficients was also studied. We will also present a method for ephemeris improvement of 1999JU3 using spacecraft relative position data and radiometric tracking measurements.
[View Full Paper]

AAS 13 – 418
(Paper Withdrawn)

AAS 13 – 423
(Paper Withdrawn)

SESSION 24: SPECIAL SESSION: MARS SCIENCE LABORATORY (MSL) III
Chair: Dr. Eric Gustafson, Jet Propulsion Laboratory

AAS 13 – 424

Powered Flight Design and Reconstructed Performance Summary for the Mars Science Laboratory Mission

Steven Sell, **Miguel San Martin** and **Frederick Serricchio**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **Jody Davis**, NASA Langley Research Center, Hampton, Virginia, U.S.A.

The Powered Flight segment of Mars Science Laboratory's (MSL) Entry, Descent, and Landing (EDL) system extends from backshell separation through landing. This segment is responsible for removing the final 0.1% of the kinetic energy dissipated during EDL and culminating with the successful touchdown of the rover on the surface of Mars. Many challenges exist in the Powered Flight segment: extraction of Powered Descent Vehicle from the backshell, performing a 300m divert maneuver to avoid the backshell and parachute, slowing the descent from 85 m/s to 0.75 m/s and successfully lowering the rover on a 7.5m bridle beneath the rocket-powered Descent Stage and gently placing it on the surface using the Sky Crane Maneuver. Finally, the nearly-spent Descent Stage must execute a Flyaway maneuver to ensure surface impact a safe distance from the Rover. This paper provides an overview of the powered flight design, key features, and event timeline. It also summarizes Curiosity's as flown performance on the night of August 5th as reconstructed by the flight team. [View Full Paper]

AAS 13 – 425

Approach and Entry, Descent, and Landing Operations for the Mars Science Laboratory Mission

Allen Chen, **Martin Greco**, **Tomas Martin-Mur**, **Brian Portock** and **Adam Steltzner**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

On August 5th, 2012, at 10:31 PM PDT, the Mars Science Laboratory (MSL) rover Curiosity landed safely within Gale Crater. Her successful landing depended not only upon the flawless execution of the numerous critical activities during the seven minute entry, descent, and landing (EDL), but also upon the operational preparations and decisions made by the flight team during approach, the final weeks, days, and hours prior to landing. During this period, decisions made by the flight team balanced operational risk to the spacecraft in flight with any resulting risks incurred during EDL as a result of those decisions. This paper summarizes the operations plans made in preparation for Approach and EDL and the as flown decisions and actions executed that balanced the operational and EDL risks and prepared the vehicle for a successful landing.
[View Full Paper]

AAS 13 – 426

The Mars Science Laboratory Entry, Descent, and Landing Flight Software

Kim P. Gostelow, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

This paper describes the design, development, and testing of the EDL program from the perspective of the software engineer. We briefly cover the overall MSL flight software organization, and then the organization of EDL itself. We discuss the timeline, the structure of the GNC code (but not the algorithms as they are covered elsewhere in this conference) and the command and telemetry interfaces. Finally, we cover testing and the influence that testability had on the EDL flight software design.
[View Full Paper]

AAS 13 – 427
(Paper Withdrawn)

AAS 13 – 428
(Paper Withdrawn)

AAS 13 – 457

Lessons Learned From the Development of the MSL Descent Stage Propulsion System

Carl S. Guernsey and **Jeffrey M. Weiss**, Propulsion, Thermal, and Materials Engineering Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Development of the MSL descent stage propulsion system required a number of new propulsion hardware developments incorporating technologies not normally found in spacecraft propulsion subsystems. These developments were driven by the relatively high (25,000 N) maximum thrust level and the requirement for precise throttling of the main engines. This paper presents lessons learned in the course of these developments, including surprises and anomalies discovered at both the component and subsystem levels. [View Full Paper]

AAS 13 – 458

Design and Development of the MSL Descent Stage Propulsion System

Jeffrey M. Weiss and **Carl S. Guernsey**, Propulsion, Thermal, and Materials Engineering Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

On August 5, 2012, The Mars Science Laboratory mission successfully landed the largest interplanetary rover ever built, Curiosity, on the surface of Mars. The Entry, Descent, and Landing (EDL) phase of this mission was by far the most complex landing ever attempted on a planetary body. The Descent Stage Propulsion System played an integral and critical role during Curiosity's EDL. The Descent Stage Propulsion System was a one of a kind hydrazine propulsion system designed specifically for the EDL phase of the MSL mission. It was designed, built, and tested at the Jet Propulsion Laboratory (JPL). The purpose of this paper is to present an overview of the design and development of the MSL Descent Stage Propulsion System. Driving requirements, system design, component selection, operational sequence of the system at Mars, new developments, and key challenges will be discussed. [View Full Paper]

AAS 13 – 459
(Paper Withdrawn)

AAS 13 – 460
(Paper Withdrawn)

AAS 13 – 461

Fabrication Assembly and Test of the Mars Science Laboratory Descent Stage Propulsion System

Morgan Parker, **Ray Baker**, **Art Casillas**, **Dellon Strommen** and **Rebekah Tanimoto**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Descent Stage Propulsion System (DSPS) is the most challenging and complex propulsion system ever built at JPL. Performance requirements, such as the entry Reaction Control System (RCS) requirements, and the terminal descent requirements (3300 N maximum thrust and ~835,000 N-s total impulse in less than a minute), required a large amount of propellant and a large number of components for a spacecraft that had to fit in a 4.5 meter aeroshell. The size and shape of the aeroshell, along with the envelope of the stowed rover, limited the configuration options for the Descent Stage structure. The configuration and mass constraints of the Descent Stage structure, along with performance requirements, drove the configuration of the DSPS. This paper will examine some of the challenges encountered and solutions developed during the fabrication, assembly, and test of the DSPS. [View Full Paper]

AAS 13 – 462
(Paper Withdrawn)

AAS 13 – 463

Managing Complexity in The MSL/Curiosity Entry, Descent, and Landing Flight Software and Avionics Verification and Validation Campaign

Aaron Stehura and **Matthew Rozek**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The complexity of the Mars Science Laboratory (MSL) mission presented the Entry, Descent, and Landing systems engineering team with many challenges in its Verification and Validation (V&V) campaign. This paper describes some of the logistical hurdles related to managing a complex set of requirements, test venues, test objectives, and analysis products in the implementation of a specific portion of the overall V&V program to test the interaction of flight software with the MSL avionics suite. Application-specific solutions to these problems are presented herein, which can be generalized to other space missions and to similar formidable systems engineering problems.
[View Full Paper]

AAS 13 – 464

Verification and Validation of the Mars Science Laboratory/Curiosity Rover Entry Descent and Landing System

Richard P. Kornfeld, **Ravi Prakash**, **Allen Chen**, **Ann S. Devereaux**, **Martin E. Greco**, **Corey C. Harmon**, **Devin M. Kipp**, **A. Miguel San Martin**, **Steven W. Sell** and **Adam D. Steltzner**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

On August 6, 2012, the Curiosity rover successfully touched down on the Martian surface setting off the most ambitious surface exploration of this planetary body. Preceding this significant step were years of design, development and testing of the Curiosity Entry, Descent and Landing (EDL) system to prepare for the most complex landing endeavor ever attempted at Mars. This paper discusses the approach and implementation of the overall EDL verification and validation (V&V) program. The overall lessons learned and conclusions described herein can serve as a pathfinder for the EDL system testing approach and implementation of future Mars landed missions. [View Full Paper]

SESSION 25:
SPACE SITUATIONAL AWARENESS AND CONJUNCTION ANALYSIS II
Chair: Dr. Ryan Russell, University of Texas at Austin

AAS 13 – 429

Application of a Laser Rangefinder for Space Object Imaging and Shape Reconstruction

Michael V. Nayak, Research, Development, Test and Evaluation Support Center (RSC), Space Development and Test Directorate, Albuquerque New Mexico, U.S.A.; **Bogdan Udrea** and **Brandon Marsella**, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.; **Jaclyn R. Beck**, Applied Energy and Technology Directorate, NASA Goddard Space Flight Center, Greenbelt Maryland, U.S.A.

This paper addresses the feasibility of using point clouds generated with a single-beam laser rangefinder (LRF) to reconstruct the three-dimensional shape of an unknown Resident Space Object (RSO), employing a combination of relative motion between the chaser and the RSO and chaser attitude motion. The first step in the analysis is the application of both an LRF and a scanning LIDAR to image and reconstruct the shape of a tri-axial ellipsoid of diffuse constant reflectivity. A single beam LRF, and a multi-beam scanning LIDAR are simulated. Next, the techniques designed above are applied to the imaging of a Resident Space Object (RSO) in the shape of generic telecommunications satellite. Various inclination and attitude maneuver test cases are explored to obtain a desired level of LRF point cloud density. The study concludes that, for error-free measurements, the LRF can effectively create sufficiently dense point clouds for various asteroid and satellite shaped SOs, with low propellant consumption, by exploiting a designed combination of Keplerian and attitude motion. Finally, the technique is further tested through inclusion of two sensor error models. Results will be applied to ARAPAIMA, a nanosatellite mission funded under the US Air Force Office of Scientific Research University Nanosat Program UNP) Cycle 8. [View Full Paper]

AAS 13 – 430

Sensitivity Analysis of the Lightcurve Measurement Model for Use in Attitude and Shape Estimation of Resident Space Objects

Laura S. Henderson and **Kamesh Subbarao**, Mechanical and Aerospace Engineering Department, University of Texas at Arlington, Texas, U.S.A.

This paper deals with the estimation of the orientation and shape/size of a resident space object (RSO). These states are estimated via an Unscented Kalman filter (UKF). This filter contains a dynamical model of the RSO as well as a measurement model. The measurement model describes the lightcurve measurement. The lightcurve is the measurable amount of sunlight reflected from the RSO to an observer on Earth. A sensitivity analysis is performed to assess whether there is information concerning the angular velocity, modified Rodrigues parameters, and the shape/size parameters in this measurement. This is done via a numerical Jacobian as well as an UKF-derived observation matrix. For the cases evaluated here it is shown that the lightcurve contains information about the attitude and the shape/size. Further, it is shown that there is no information regarding the angular velocity. The estimation of this state is possible due to the dynamical model and the lightcurve measurement within the filter framework. An observability analysis is also performed on the attitude states and shape/size parameters. A singular value decomposition (SVD) of the linearized observability matrix for a batch of measurements is performed and an observability degree is obtained by identifying the maximum singular value from the SVD. The results are summarized for various initial conditions of the RSO's attitude and angular velocity states. [View Full Paper]

AAS 13 – 431

An AEGIS-FISST Sensor Management Approach for Joint Detection and Tracking in SSA

I. I. Hussein, Department of Mechanical Engineering, University of New Mexico, Albuquerque, New Mexico, U.S.A.; **R. S. Erwin** and **M. K. Jah**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

In Space Situational Awareness (SSA) not only is it desired to maintain the two line elements of objects that have already been detected, but it is also desired to maintain the catalogue by updating it whenever new objects are detected for the first time. Hence, one of the main goals of SSA is to search for and detect new objects. The main challenge to achieving this goal is the fact that the sensor resources available in the SSA system are very limited compared to the very large size of the search space and number of objects. This search and detection task needs to be performed using sensors that are often the same ones used for maintaining the tracks of detected objects. These two tasks (search and detection on one hand and tracking on the other) are two tasks that compete for the same sensor resources. Our goal is to develop information-based metrics for sensor allocation for the joint detection and tracking problem. Conventional information-based approaches to the sensor allocation problem are mostly dedicated to the problem of sensor allocation for multi-object tracking (without detection). Finite Set Statistics (FISST) is an inference approach that allows for solving the detection and tracking problems jointly. It also allows for formulating information metrics that can be used to optimize between the search/detection task and the tracking task. In this paper, we demonstrate the use of FISST-based information gain metrics for sensor allocation using a simple single-object SSA detection and tracking problem. Future work will focus on generalizing this present result to sensor allocation for multi-object detection and tracking. [View Full Paper]

AAS 13 – 432

An AEGIS-FISST Algorithm for Joint Detection, Classification and Tracking

I. I. Hussein, Department of Mechanical Engineering, University of New Mexico, Albuquerque, New Mexico, U.S.A.; **C. Früh**, **R. S. Erwin** and **M. K. Jah**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

Space Situational Awareness requires the acquisition, cataloging, retrieval and predictive use of a large amount of data pertaining to the existence, character, and orbital state of all objects in Earth orbit. About five hundred thousand objects one centimeter in size or larger populate the space around earth, which increases the need for new methods and techniques that can contribute to the core tasks of SSA: discovery of new objects, tracking of (possibly maneuverable) detected objects, and classification of tracked objects. A key feature of the SSA problem is the fact that these tasks are interdependent. This interdependence between hybrid continuous and discrete estimation variables makes the joint detection, classification and tracking inference problem (JDCT) coupled. One method that takes into account such interdependencies is the Finite Set Statistical (FISST) hybrid multi-target estimation approach and its derivative methods. In this paper we derive the multi-target multi-class FISST (MTMC FISST) filter as well as a Gaussian mixture-based closed-form approximation to the filter, resulting in the MTMC AEGIS-FISST filter. As a proof of concept, we demonstrate the main result using a simple single-object, dual-class SSA problem. [View Full Paper]

AAS 13 – 433

Comparing the Reid Cost to the Mahalanobis Distance for Uncorrelated Track Association

C. Channing Chow and **Keric Hill**, Pacific Defense Solutions, LLC., Kihei, Hawaii, U.S.A.; **Joshua Horwood**, Numerica Corporation, Loveland, Colorado, U.S.A.; **Chris Sabol**, Air Force Maui Optical and Supercomputing, Air Force Research Laboratory, Kihei, Hawaii, U.S.A.

A central problem faced by the space surveillance community is the problem of track-to-track association. Under Gaussian assumptions a track state can be characterized by its first two moments (mean and covariance). As such, the Mahalanobis distance is commonly used to parameterize the correlation of data sets. However, naive summations of information yield large association hypervolumes that increase the likelihood of false alarms. The Reid cost instead scales the product of the probability densities of both tracks by a third fused estimate. Simulations of 1000 space objects show tremendous improvement in resolving associations when using Reid's function.
[View Full Paper]

AAS 13 – 434

Orbit Determination of an Uncooperative RSO Using a Stereo Vision-Based Sensor

Bharat Mahajan, **Henry J. Pernicka** and **Jacob Darling**, Mechanical and Aerospace Engineering, Missouri University of Science & Technology, Rolla, Missouri, U.S.A.

Space Situational Awareness (SSA) involves the capability of identification, tracking and characterization of resident space objects. This study considers the use of an inspector spacecraft to autonomously determine the orbit and ballistic coefficient of a resident space object (RSO) in real-time using a stereo vision-based relative navigation sensor when in close proximity with the RSO. Additionally, the inspector spacecraft performs a leader-follower and circumnavigation type formations with the RSO to facilitate 3-D reconstruction of its shape from the visual images. An Unscented Kalman Filter (UKF) is formulated to process raw measurements in the two-dimensional pixel coordinate frame from the visual images of the RSO. The UKF produces relative orbit estimates of the RSO with respect to the inspector in addition to its ballistic coefficient. The UKF uses a novel formulation of relative dynamics that includes differential drag effects and applied thrust accelerations by the inspector spacecraft. The inspector's own orbit and ballistic coefficient are estimated by processing raw GPS pseudorange measurements using an Extended Kalman Filter. The inspector's orbit estimates can be fused with the relative orbit estimates of the RSO to autonomously determine the orbital elements of the RSO. A linear optimal controller is formulated to enable the inspector spacecraft to maintain the RSO in field-of-view of the two cameras as well as to perform leader-follower and circumnavigation type formations. Simulation results showing the feasibility of using stereo vision-based sensors for meeting the above stated SSA objectives and proximity operations are presented. [View Full Paper]

AAS 13 – 435

Operating Characteristic Approach to Effective Satellite Conjunction Filtering

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

This paper extends concepts of signal detection theory to examine the performance of conjunction screening techniques. The most effective way to identify satellites likely to collide is to employ filters to isolate 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. The three most common filters are the apogee/perigee, orbit path, and time. The apogee/perigee filter eliminates pairings that lack overlap in the respective ranges of radius values regardless of planar orientation. The orbit path filter (also known as the geometric pre-filter) takes planar orientation into account 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. The time filter identifies pairs that have survived other screening processes but are unlikely to be in close proximity during the analysis interval. The workings of each filter are summarized and then tested with various threshold and pad settings. Every filtering process is vulnerable to Type I and Type II errors, admitting infeasible conjunctions and missing feasible conjunctions. Documenting Type I and Type II errors using an Operating Characteristic approach guides selection of the best operating point for the filters. This work provides a formalism for selecting filter parameters. [View Full Paper]

AAS 13 – 436

Optimal Impulsive Collision Avoidance

Claudio Bombardelli, Space Dynamics Group, Technical University of Madrid (UPM), Madrid, Spain

The problem of optimal impulsive collision avoidance between two colliding objects in 3-dimensional elliptical Keplerian orbits is investigated with the purpose of establishing the optimal impulse direction and orbit location that give rise to the maximum miss distance following the maneuver. Closed-form analytical expressions are provided that predicts such distance and can be employed to perform a full optimization analysis. After verifying the accuracy of the expression for any orbital eccentricity and encounter geometry the optimum maneuver direction is derived as a function of the arc length separation between the maneuver point and the predicted collision point. The provided formulas can be used for high-accuracy instantaneous estimation of the outcome of a generic impulsive collision avoidance maneuver and its optimization.
[View Full Paper]

AAS 13 – 437
(Paper Withdrawn)

SESSION 26:
ATTITUDE DETERMINATION, DYNAMICS, AND CONTROL IV
Chair: Dr. Maruthi R. Akella, The University of Texas at Austin

AAS 13 – 210

CubeSat Attitude Control Systems With Magnetic Torquers and Flywheel

Junquan Li, **Mark A. Post** and **Regina Lee**, Department of Earth and Space Engineering, York University, Toronto, Ontario, Canada

The accuracy of nanosatellite attitude control using only pure magnetic actuators is low and on the order less than 5 degrees. The main reason is that the magnetic torque is only orthogonal to the instantaneous direction of the Earth's magnetic field. In this paper, the pure magnetic control and hybrid magnetic control numerical simulations are presented for nadir and limb pointing. The results show that precise attitude tracking can be reached using hybrid magnetic control which uses three magnetic actuators and one reaction wheel. The hybrid magnetic control accuracy using an adaptive sliding mode attitude control algorithm is less than 0.5 degree. [View Full Paper]

AAS 13 – 475

An Accurate and Efficient Gaussian Fit Centroiding Algorithm for Star Trackers

Tjorven Delabie, **Joris De Schutter** and **Bart Vandenbussche**, Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300B, Heverlee, Belgium

This paper presents a novel centroiding algorithm for star trackers. The proposed algorithm, which is referred to as the Gaussian Grid algorithm, fits an elliptical Gaussian function to the measured pixel data and derives explicit expressions to determine the centroids of the stars. In tests, the algorithm proved to yield accuracy comparable to that of the most accurate existing algorithms, while being significantly less computationally intensive. This reduction in computational cost allows to improve performance by acquiring the attitude estimates at a higher rate or use more stars in the estimation algorithms. It is also a valuable contribution to the expanding field of small satellites, where it could enable low-cost platforms to have highly accurate attitude estimation.
[View Full Paper]

AAS 13 – 476

Attitude Determination for the Van Allen Probes

Adam M. Fosbury, **Gabe D. Rogers**, **John H. Wirzburger**, **Madeline N. Kirk** and **J. Courtney Ray**, The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

This paper describes the ground-based attitude estimation system used by the Van Allen Probes. This system consists of three algorithms with varying levels of fidelity and complexity. Attitude estimation results from each algorithm are presented along with descriptions of, and solutions to, challenges encountered during the commissioning period. Results have had better than expected accuracy, surpassing the spacecraft's requirements. [View Full Paper]

AAS 13 – 478

Sigma Point Transformation for Gaussian Mixture Distributions Applied to Attitude Estimation

Richard Linares and **John L. Crassidis**, Department of Mechanical and Aerospace Engineering, University at Buffalo, The State University of New York, Buffalo, New York, U.S.A.

This paper describes the development of an approximate method for propagating uncertainty through stochastic dynamical systems using a quadrature rule integration based method. The development of quadrature rules for Gaussian mixture distributions is discussed. A numerical solution to this problem is considered that uses a Gram-Schmidt process. The new approach is applied to the attitude estimation problem. The proposed method outperforms the unscented Kalman filter for attitude estimation for scenario with large initial error. [View Full Paper]

AAS 13 – 479

Optimization of Directional Sensor Orientation With Application to Photodiodes for Spacecraft Attitude Determination

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

We present a method to optimize the orientation of directional sensors and instruments in a vehicle body-fixed frame. This technique can be used in spacecraft design to maximize the performance of directional sensors and instruments. The optimization formulation consists of using the attitude sphere to create directions over which to optimize and deriving an objective function that uses these directions along with their weights. The optimization method is presented and demonstrated by application to photodiodes for spacecraft attitude determination, in which the orientation of the photodiodes are optimized to provide the most accurate sun vector estimates with the given hardware. This technique maximizes subsystem performance and provides a design method to replace traditional, iterative design approaches to sensor placement.
[View Full Paper]

AAS 13 – 481

Nanosatellite Sun Sensor Attitude Determination Using Low-Cost Hardware

Mark A. Post, **Junquan Li** and **Regina Lee**, Department of Earth and Space Engineering, York University, Toronto, Ontario, Canada

This paper outlines the development of two coarse sun sensor methodologies that are compact and efficient enough for a CubeSat-class nanosatellite: direct measurement of the solar angle using a photodiode array sensor, and estimation of the solar angle using current measurements from an array of solar cells. An overview of the technology and hardware designs used is provided in the context of a university nanosatellite development program. Testing results from the sun sensors on a laboratory attitude control system are used to validate and compare the performance of the two methodologies for nanosatellite attitude control. [View Full Paper]

AAS 13 – 482

Sensor Calibration for the Microscope Satellite Mission

Hanns Selig and **Claus Lämmerzahl**, ZARM Center of Applied Space Technology and Microgravity, University of Bremen, Germany

The MICROSCOPE drag free satellite mission (launch in 2016) will perform a test of the universality of free fall (Equivalence Principle - EP) to an new level of accuracy. The payload consists of two sensors, each controlling the free fall of a pair of test masses. The EP test strongly depends on the rejection of disturbances arising from the coupling and misalignments of the instrument vectorial outputs. Therefore the performance of the mission depends on the success of the calibration operations which are planned during the satellite life in orbit, as well as on ground at the ZARM drop tower.
[View Full Paper]

AAS 13 – 485

Attitude and Orbit Propagation of High Area-to-Mass Ratio (HAMR) Objects Using a Semi-Coupled Approach

Carolin Früh and **Moriba K. Jah**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

In this paper a new approach is presented to propagate the attitude and orbital motion of objects with high area-to-mass ratios (HAMR) in near geostationary orbit in a semi-coupled approach. To ease the computational burden and allow real time applications, orbit and attitude motion are not propagated as fully coupled system, but only initialized as fully coupled and then decoupled and propagated independently, using the values derived in the initialization step as a priori values. Entropy serves as a double metric and the system is triggered to re-coupled again for a single epoch, as soon as the a priori attitude and integrated attitude or a priori orbit motion and integrated attitude motion deviate significantly. In a second approach Kullback-Leibler divergence is used as a trigger. Both the entropy and the Kullback-Leibler divergence based method is compared to the fully coupled integration solution. [View Full Paper]

SESSION 27: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL II
Chair: Dr. Marcus Holzinger, Georgia Institute of Technology

AAS 13 – 438
Precision Landing at Mars Using Discrete-Event Drag Modulation

Zachary R. Putnam and **Robert D. Braun**, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.

An entry, descent, and landing architecture capable of achieving Mars Science Laboratory class landed accuracy (with 10 km of target) while delivering a Mars Exploration Rover class payload to the surface of Mars is presented. The architecture consists of a Mars Exploration Rover class aeroshell with a rigid, annular drag skirt. Maximum vehicle diameter is limited to be compatible with current launch vehicle fairings. A single drag skirt jettison event is used to control range during entry. Three-degree-of-freedom trajectory simulation is used in conjunction with Monte Carlo techniques to assess the flight performance of the proposed architecture. Results indicate landed accuracy is competitive with pre-flight Mars Science Laboratory estimates, and peak heat rate and integrated heat load are significantly reduced relative to the Mars Exploration Rover entry system. Modeling parachute descent within the onboard guidance algorithm is found to remove range error bias present at touchdown; the addition of a range-based parachute deploy trigger is found to significantly improve landed accuracy.
[View Full Paper]

AAS 13 – 439
Decentralized Model Predictive Control of Swarms of Spacecraft Using Sequential Convex Programming

Daniel Morgan and **Soon-Jo Chung**, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.;
Fred Y. Hadaegh, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

This paper presents a decentralized, model predictive control algorithm for the reconfiguration of swarms of spacecraft composed of hundreds to thousands of agents with limited capabilities. In our prior work, sequential convex programming has been used to determine collision-free, fuel-efficient trajectories for the reconfiguration of spacecraft swarms. This paper uses a model predictive control approach to implement the sequential convex programming algorithm in real-time. By updating the optimal trajectories during the reconfiguration, the model predictive control algorithm results in decentralized computations and communication between neighboring spacecraft only. Additionally, model predictive control reduces the horizon of the convex optimizations, which reduces the run time of the algorithm. [View Full Paper]

AAS 13 – 440

Spacecraft Maneuvering Via Atmospheric Differential Drag Using an Adaptive Lyapunov Controller

D. Pérez and **R. Bevilacqua**, Mechanical, Aerospace and Nuclear Engineering Department, Rensselaer Polytechnic Institute (RPI), Troy, New York, U.S.A.

An atmospheric differential drag based adaptive Lyapunov controller, originally proposed by the authors in previous work for spacecraft rendezvous, is here generalized allowing for the tracking of reference trajectories or dynamics. Differential drag is based on the ability to vary a satellite's cross wind surface area, and it represents a propellant-free alternative to thrusters to control relative motion of low Earth orbiting spacecraft. The interest in autonomous propellant-less maneuvering comes from the desire of reducing costs of performing formation maneuvering. Formation maneuvering opens up a wide variety of new applications for spacecraft, such as on-orbit maintenance missions and refueling. The control technique is successfully tested using Systems Tool Kit simulations for re-phase, fly-around, and rendezvous maneuvers, proving the feasibility of the proposed approach for a real flight. [View Full Paper]

AAS 13 – 441

Model Diagnostics and Dynamic Emulation: Enhancing the Understanding and Impact of Complex Models in Systems Engineering

Ryan E. G. McKennon-Kelly and **Matthew P. Ferringer**, The Aerospace Corporation, Chantilly, Virginia, U.S.A.; **Patrick M. Reed**, Department of Civil and Environmental Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.; **David B. Spencer**, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.

This paper proposes and demonstrates sensitivity-informed *model diagnostics* as applied to constellation design (CD). Model diagnostics provide guidance on how high fidelity, computationally intensive, simulations can be simplified to yield substantial computational savings while minimally impacting accuracy. Moreover, current CD methods average performance at multiple locations across the globe over a year; preventing nuanced evaluation of systems, and the tailoring of design for specific applications. Model diagnostics discovered the most important inputs, times, and locations for analysis; highlighting key dynamics typically occluded by averaging. Model diagnostics benefits are demonstrated in this study with a specific example of guiding the creation of *dynamic emulators*, with significant potential for improving the computational tractability of design optimization. [View Full Paper]

AAS 13 – 442

Simulation and Analysis of a Phobos-Anchored Tether

Andrew T. Klesh, **Eric D. Gustafson**, **Nathan Strange** and **Brian Wilcox**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

We investigate the dynamics and feasibility of a light-weight tether anchored to Phobos near Stickney crater. The tether is initially deployed along the Mars-Phobos line with its tip sitting beyond the Mars-Phobos L1 point. Such a tether could potentially provide a stable, low-gravity anchor point for human or robotic missions, or serve as an elevator for Phobos resources. Unfortunately trajectories near the L1 point are unstable, and there are proportionally large disturbance forces. We model the tether and simulate the evolution of its position to determine the feasibility and potential control needs of implementation. [View Full Paper]

AAS 13 – 444

Spacecraft Navigation Using Celestial Gamma-Ray Sources

Chuck S. Hisamoto and **Suneel I. Sheikh**, ASTER Labs, Inc., Shoreview, Minnesota, U.S.A.

As the future of space exploration endeavors progresses, spacecraft that are capable of autonomously determining their position and velocity will provide clear navigation advances to mission operations. Thus, new techniques for determining spacecraft navigation solutions using celestial gamma-ray sources have been developed. Most of these sources offer detectable, bright, high-energy events that provide well-defined characteristics conducive to accurate time-alignment among spatially separated spacecraft. Utilizing assemblages of photons from distant gamma-ray bursts, relative range between two spacecraft can be accurately computed along the direction to each burst's source based upon the difference in arrival time of the burst emission at each spacecraft's location. Correlation methods used to time-align the high-energy burst profiles are provided. A simulation of the newly devised navigation algorithms has been developed to assess the system's potential performance. Using predicted observation capabilities for this system, the analysis demonstrates position uncertainties comparable to the NASA Deep Space Network for deep space trajectories. [View Full Paper]

AAS 13 – 445

Station-Keeping Strategies for Satellite Constellation

CUI Hongzheng, **TANG Geshi**, Flight Dynamics Laboratory, Beijing Aerospace Control Center, Beijing, China; **YIN Jianfeng**, **HUANG Hao** and **HAN Chao**, School of Astronautics, Beihang University, Beijing, China

This paper firstly introduces the concepts on control box and control reference for absolute and relative station-keeping, how to determine the control reference, and the uniform control flow for different station-keeping strategies. And then, studies the different station-keeping control-laws for Walker constellation, including different orbital regions. The demonstration experiments concerning different station-keeping strategies are carried out with initial orbit element errors and control tolerance based on Constellation Station Keeping Kit (CSKK), which is recently designed and developed at BACC for satellite constellation operation demonstration. [View Full Paper]

AAS 13 – 446
(Paper Withdrawn)

AAS 13 – 487
(Paper Withdrawn)

SESSION 28: MISSION/MANEUVER DESIGN
Chair: Dr. Rodney Anderson, Jet Propulsion Laboratory

AAS 13 – 447
Modelling and Simulation of the Microscope Mission

Meike List, **Stefanie Bremer** and **Benny Rievers**, Fundamental Physics Department, ZARM, University of Bremen, Germany

The French space mission MICROSCOPE (MICRO Satellite à traînée Componsée pour l'Obversation du Principe d'Equivalence) aims at testing the WEP (weak equivalence principle) up to an accuracy of the Eötvös parameter $\eta = 10^{-15}$. With the help of two high-precision capacitive differential accelerometers, which are designed and built by the French institute ONERA (Office National d'Etudes et Recherches Aérospatiales), the desired high precision level of the measurement will be provided.

At ZARM (Center of Applied Space Technology and Microgravity), which is member of the mission's performance team, the upcoming data evaluation process is prepared by using the HPS (High Performance satellite dynamics Simulator). This tool is developed in cooperation with the DLR Institute of Space Systems in Bremen. The HPS includes possibilities for modelling spacecraft and test mass dynamics as well as disturbances due to the interaction of the satellite with its space environment (e.g. solar radiation pressure) and mission specific design aspects (e.g. geometry, coupling effects). Thus, a comprehensive simulator of the real system including the science signal and all error sources can be built.

In this work, the effects of solar radiation pressure disturbing the purely gravitationally determined trajectory of the satellite and the test masses, respectively, is analyzed. [View Full Paper]

AAS 13 – 448
(Paper Withdrawn)

AAS 13 – 449

Orbital Transfer Techniques for Round-Trip Mars Missions

Damon Landau, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The human exploration of Phobos and Deimos or the retrieval of a surface sample launched to low-Mars orbit presents a highly constrained orbital transfer problem. In general, the plane of the target orbit will not be accessible from the arrival or departure interplanetary trajectories with an (energetically optimal) tangential burn at periapsis. The orbital design is further complicated by the addition of a high-energy parking orbit for the relatively massive Deep Space Vehicle to reduce propellant expenditure, while the crew transfers to and from the target orbit in a smaller Space Exploration Vehicle. The proposed strategy shifts the arrival and departure maneuvers away from periapsis so that the apsidal line of the parking orbit lies in the plane of the target orbit, permitting highly efficient plane change maneuvers at apoapsis of the elliptical parking orbit. An apsidal shift during the arrival or departure maneuver is approximately five times as efficient as maneuvering while in Mars orbit, thus significantly reducing the propellant necessary to transfer between the arrival, target, and departure orbits. [View Full Paper]

AAS 13 – 450
(Paper Withdrawn)

AAS 13 – 451

Optimal Mixed Impulsive and Continuous Thrust Trajectories to the Interior Earth-Moon L_1 Lagrange Point

Daero Lee, **Eric A. Butcher** and **Amit K. Sanyal**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.

Optimal transfer trajectories are designed for a spacecraft using mixed impulsive and continuous thrust propulsion to depart low-Earth orbit and enter a specified planar Lyapunov orbit at the interior Earth-Moon Lagrange point in the frame-work of the planar Circular Restricted Three Body Problem. The flight time and impulsive/continuous thrust weighting factor are specified in advance, while the results from two separate performance indices based on minimum fuel and minimum control energy are compared. The continuous dynamic optimization problem is reformulated as a discrete optimization through direct transcription and collocation, which then is solved using nonlinear programming software. The optimal transfer trajectory results are analyzed using trade-off studies. [View Full Paper]

AAS 13 – 452

The Plans for Getting OCO-2 into Orbit

Mark A. Vincent, Navigation & Mission Design, Pasadena, California, U.S.A.;
Mark D. Garcia, Mission Design & Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The method and terms used to design the target parameters that will be used to insert the Orbiting Carbon Observatory 2 (OCO-2) into the A-train are defined. Comparisons are made to the plan that would have been used had OCO-1 successfully achieved its Injection Orbit. Major differences arise from the fact that OCO-1 was launched on a Taurus XL with a target 65 km below the A-Train while OCO-2 will be launched on a Delta II with a target only 15 km below the A-Train. The new plan is similar to the one used for the CloudSat/CALIPSO missions, but reformulated into a one-step iteration process that is easier to understand. [View Full Paper]

AAS 13 – 453

(Paper Withdrawn)

AAS 13 – 454

Mission Design for NASA's Van Allen Probes Mission

Fazle E. Siddique and **Gene A. Heyler**, The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

The Van Allen Probes mission, part of NASA's Living With a Star Program, successfully launched on August 30th, 2012 from the Cape Canaveral Atlas-V Space Launch Complex 41. The two year mission consists of two spin stabilized spacecraft in highly eccentric Earth orbits that provide insight into the dynamics of Earth's radiation belts. The observatories were designed, built, and operated by the Johns Hopkins University Applied Physics Laboratory. The two spacecraft were launched on a single Atlas V 401 launch vehicle, and placed in orbits that cause one spacecraft to lap the other approximately four times per year. This paper describes the spacecraft and instruments, the pertinent science requirements that influenced the trajectory design, the launch vehicle windows and targeting, and explains some of the unique features of the orbit evolution to achieve requirements. Also addressed is the post-separation trajectory correction rationale and notional end-of-life decommissioning plans. [View Full Paper]

AAS 13 – 455

Ongoing Mission Analysis for the Solar Terrestrial Relations Observatory (STEREO)

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

The state of mission analysis for the ongoing Solar TErrestrial RElations Observatory is presented. Recent developments include the construction of a 20-year predictive ephemeris that compares modeling sensitivity and a detrending analysis for the coefficient of solar reflectivity. Hypothetical mission extension options are studied given the remaining fuel on each of the spacecraft, including small-body flybys and Earth-moon system capture. All small-bodies that pass nearby both satellites are considered for flyby targeting. High-fidelity end-to-end mission design scenarios are presented.
[View Full Paper]

AAS 13 – 456

Orbital Accessibility Problem With a Single Impulse

Changxuan Wen, **Yushan Zhao** and **Peng Shi**, School of Astronautics, Beihang University, Haidian District, Beijing, China

The orbital accessibility problem (OAP) for spacecraft under a single impulsive maneuver is studied. A geometrical description of the accessible condition is attained by using the terminal velocity hyperbola of the orbital two point boundary value problem (TPBVP). This geometrical description is further converted to an algebraic one through analytic geometry for the convenience of numerical computation. The OAP to a special collinear target is also considered and can be determined through a collinear accessibility function. Three typical applications are suggested: (1) to solve the OAP when both the impulse magnitude and the target position are specified, (2) to search the minimum impulse required when only the target position is given, and (3) to calculate the reachable domain (RD) when only the impulse magnitude is given. The RD is the first accurate solution in the three-dimensional space. Numerical examples are presented to validate the proposition and demonstrate the three typical applications. [View Full Paper]

AAS 13 – 466

Lyapunov-Floquet Transformation of Satellite Relative Motion in Elliptic Orbits

Ryan E. Sherrill and **Andrew J. Sinclair**, Aerospace Engineering Department, Auburn University, Auburn, Alabama, U.S.A.; **S. C. Sinha**, Mechanical Engineering Department, Auburn University, Auburn, Alabama, U.S.A.;
T. Alan Lovell, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

The relative motion between chief and deputy satellites in close proximity with orbits of arbitrary eccentricity can be described by linearized time-periodic equations of motion. The linear time-invariant Hill-Clohessy-Wiltshire equations are typically derived from these equations by assuming the chief satellite is in a circular orbit. Three different transformations are here presented which relate the linearized time-varying equations of relative motion to the Hill-Clohessy-Wiltshire equations through coordinate transformations. These transformations allow the Hill-Clohessy-Wiltshire equations to describe the relative motion for a chief orbit of any eccentricity. [View Full Paper]

AAS 13 – 467

Calibration of Linearized Solutions for Satellite Relative Motion

Andrew J. Sinclair and **Ryan E. Sherrill**, Aerospace Engineering Department, Auburn University, Auburn, Alabama, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

The motion of a deputy satellite relative to a chief satellite can be described with either Cartesian coordinates or orbital-element differences. For close proximity, both descriptions can be linearized. An underappreciated fact is that the linearized descriptions are equivalent: the linearized transformation between the two solves the linearized dynamics. This suggests a calibrated initial condition for linearized Cartesian propagation that is related to the orbital-element differences by the linearized transformation. This calibration greatly increases the domain of validity of the linearized approximation, and provides far greater accuracy in matching the nonlinear solution over a larger range of separations. [View Full Paper]

AAS 13 – 468
(Paper Withdrawn)

DIRK BROUWER AWARD PLENARY LECTURE

AAS 13 – 499

The Mechanics of Exploring Asteroids (Abstract and Biography Only)

Daniel J. Scheeres, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, The University of Colorado, Boulder, Colorado, U.S.A.

The exploration of asteroids using spacecraft is motivated by significant themes: the scientific study of solar system formation and evolution, the exploration of the solar system, and the protection of society against future hazardous impactors. This endeavor involves significant challenges across a range of technical issues: development of new models for mathematically describing the environment, understanding the basic mechanics of asteroids, and describing and predicting orbital motion in these highly perturbed environments. This talk will introduce the technical challenges the asteroid environment poses, review progress which has occurred over the last two decades, and indicate where research is still needed. [View Full Summary]

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