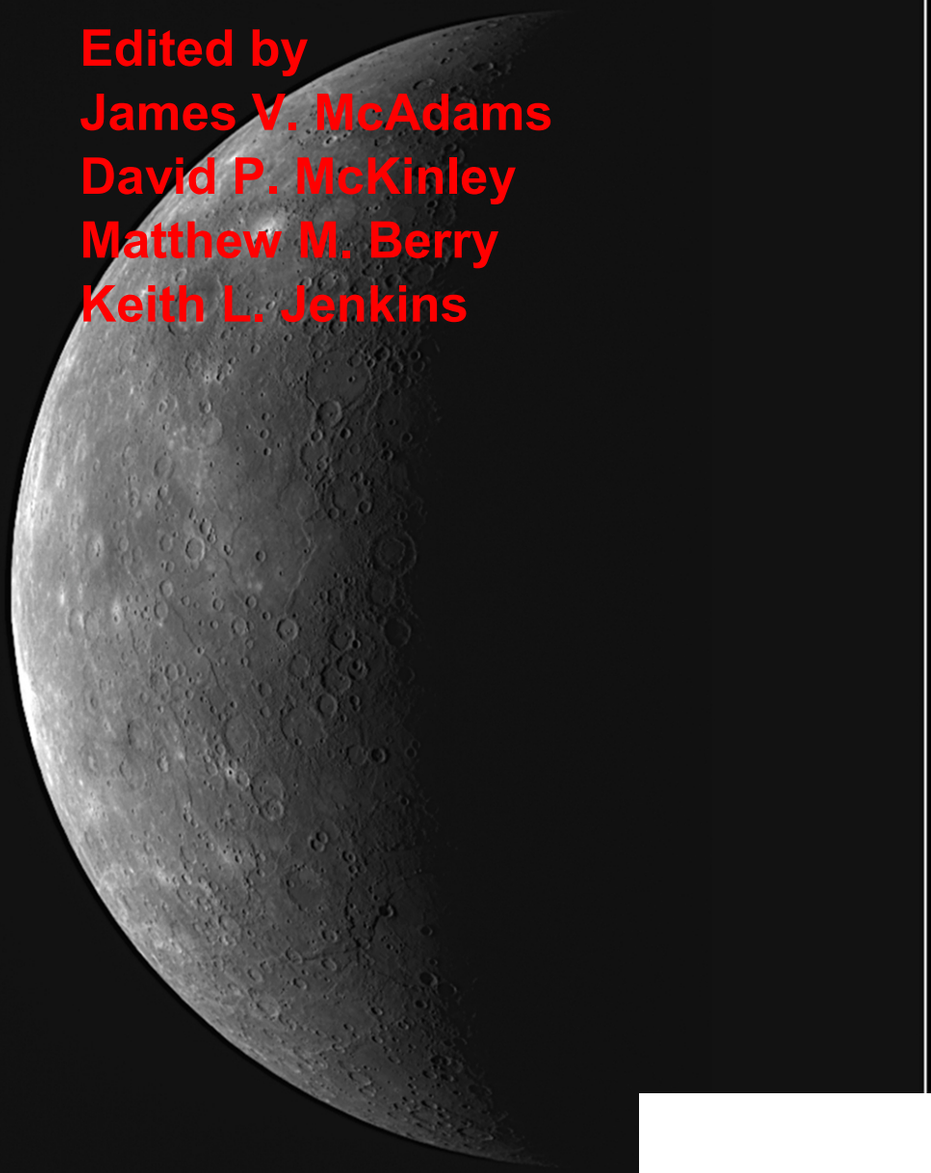
SPACEFLIGHT MECHANICS 2012

Edited by
James V. McAdams
David P. McKinley
Matthew M. Berry
Keith L. Jenkins



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Volume 143
ADVANCES IN THE ASTRONAUTICAL SCIENCES

SPACEFLIGHT MECHANICS 2012

Front Cover Illustration:

In March 2011, MESSENGER became the first spacecraft to orbit the planet Mercury. In July of the same year, the Dawn spacecraft became the first to orbit a main-belt asteroid, Vesta. Both MESSENGER and Dawn are missions in NASA's Discovery program.

MESSENGER Mercury image credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.
Dawn Vesta image credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.

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FOREWORD

This volume is the twenty-second 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 III of the hard copy volume lists proceedings available through the American Astronautical Society.

Spaceflight Mechanics 2012, Volume 143, Advances in the Astronautical Sciences, consists of three parts totaling about 2,612 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 third 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 our editors.

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 2012 appears as Volume 143, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the 22nd AAS/AIAA Space Flight Mechanics Meeting 2012.

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

Spaceflight Mechanics 2010, Volume 136, *Advances in the Astronautical Sciences*, Eds. D. Mortari et al., 2652p., three parts, plus a CD ROM supplement.

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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 22nd Space Flight Mechanics Meeting was held at the Francis Marion Hotel in Charleston, South Carolina, January 29 to February 2, 2012. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. The 191 people registered for the meeting included 85 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 154 technical papers presented in 22 sessions on topics related to spaceflight mechanics and astrodynamics. There were no special sessions for this conference.

The meeting included three social events. An early bird reception was held at the Francis Marion Hotel on Sunday evening, January 29. This well attended function provided an opportunity for conference attendees and their guests to socialize over catered food and drink. An awards ceremony and Dirk Brower Award lecture was held after the completion of all sessions late on Tuesday afternoon, January 31. Attendees were treated to a presentation entitled "Review of Quadrilateralized Spherical Cube and Views of Future Work on Spacecraft Collisions" by Brouwer Award winner Dr. Ken Chan. The final social event, held onboard the 888-foot-long USS Yorktowm aircraft carrier in Charleston Harbor on Tuesday evening, included guided and self-guided tours of the aircraft carrier and its many museum and memorial displays, as well as a low country style dinner buffet. Many guests experienced an onboard flight simulator as part of this memorable offsite social event.

The editors extend their gratitude to the Session Chairs who made this meeting successful: Xiaoli Bai, Shyam Bhaskaran, Angela Bowes, William (Todd) Cerven, Yanping Guo, Marcus Holzinger, Felix Hoots, Don Mackison, Laurie Mann, Robert Melton, Lauri Newman, Lisa Policastri, Anil Rao, Ryan Russell, John Seago, David Spencer, Tom Starchville, Sergei Tanygin, Aaron Trask, Matthew Wilkins, Ken Williams, and Roby Wilson. Our gratitude also goes to Hanspeter Schaub and Shannon Coffey for conference website postings and 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 printing of the conference programs.

James V. McAdams
Johns Hopkins University
Applied Physics Laboratory
AAS Technical Chair

David P. McKinley
a.i. solutions, Inc.
AIAA Technical Chair

Dr. Matthew M. Berry
Analytical Graphics, Inc.
AAS General Chair

Mr. Keith L. Jenkins, Esq.
Keith L. Jenkins, Registered Patent Attorney, LLC
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SESSION 1: FORMATION FLYING I
Chair: Dr. Aaron Trask, Apogee Integration

AAS 12 – 100
Early Formation Design Using a Geometrical Approach

Jason L. Tichy, a.i. solutions, Inc., Lanham, Maryland, U.S.A.

A new approach to formation design adopts a Keplerian concept to modify the path geometry of the orbit. The state propagation problem is simplified by transforming an orbit into an ellipse and using Keplerian elements to describe the path of the spacecraft. Because the parametric form of an ellipse is based on eccentric anomaly, Kepler's equation is exploited to associate position and time, enabling the formation design to stage the spacecraft's location on its perspective ellipse. The optimization problem is then formulated to solve for an elliptical orientation relative to a reference ellipse, as well as stage each location on the ellipse associated by an instant in time. The result is an algorithm that generates formations similar to those generated by a Cartesian-based counterpart. Also, because the geometrical solution describes the full path of the orbit, clear methods exist for including perturbations. The solution geometry, transformed by means of Brouwer-Lyddane perturbation methods for example, is demonstrated to transition into models of higher fidelity. Results indicate that this technique can lengthen the sustainability of formation quality in the presence of varying perturbations. This method to design formations using the geometrical path manipulation simplifies the problem, makes the problem more robust to the initial state, and greatly reduces the computations employed in the formation design. [View Full Paper]

AAS 12 – 101
Effects of Staggering Formation Maneuvers on the Magnetospheric Multi-Scale Mission Trajectories

Khashayar Parsay and **Laurie Mann**, a.i. solutions, Inc., Lanham, Maryland, U.S.A.

Formation maneuvering for the MMS mission is accomplished by executing a two-burn transfer for each spacecraft to achieve a set of desired states. Because the same radio frequency is shared by all four spacecraft, only one spacecraft can execute a maneuver at any given time. Therefore, the maneuver execution epochs for the MMS spacecraft must be staggered. The selection of the staggered maneuver sequence has a significant effect on the propellant usage and the spacecraft close-approach profile. A method for selecting a favorable maneuver sequence is proposed and measured in terms of propellant and safety. [View Full Paper]

AAS 12 – 102

Formation Maneuver Planning for Collision Avoidance and Direction Coverage

Liam M. Healy and **C. Glen Henshaw**, Naval Research Laboratory, Washington DC, U.S.A.

In order to assist guidance techniques for a free-flying inspection vehicle, we develop a technique to solve analytically in closed form the three-point periodic boundary value problem for relative motion about a circular primary for solutions that are periodic or non-drifting, i.e., the orbital periods of the two vehicles are equal. We show how to compute impulsive maneuvers in the primary radial and cross-track directions, and discuss how to parametrize these maneuvers and obtain solutions that satisfy constraints, for example collision avoidance or direction of coverage, or optimize quantities, such as time or fuel usage. In order to do these calculations, we use apocentral coordinates and a set of four relative orbital parameters we developed earlier. We separate change in relative velocity (maneuvers) into radial and cross-track components and use a waypoint technique to plan the maneuvers. [View Full Paper]

AAS 12 – 103

A Lyapunov-Floquet Generalization of the Hill-Clohessy-Wiltshire Equations

Ryan E. Sherrill and **Andrew J. Sinclair**, 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 relative motion between chief and deputy satellites in close proximity in orbits of arbitrary eccentricity can be described by linearized time-varying 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. However, a Lyapunov-Floquet transformation relates the linearized equations of relative motion to the Hill-Clohessy-Wiltshire equations through a periodic coordinate transformation for any elliptic orbit. This transformation is based on the invariant form of the Tschauner-Hempel equations, and evaluates the Hill-Clohessy-Wiltshire equations at a virtual time. [View Full Paper]

AAS 12 – 104

Optimal Reconfigurations of Coulomb Formations Along Invariant Manifolds

D. R. Jones, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.

Coulomb formations refer to swarms of closely-flying spacecraft, in which the net electric charge of each vehicle is controlled. Active charge control is central to this concept and enables a propulsion system with highly desirable characteristics, albeit with limited controllability. Numerous Coulomb equilibria have been derived (for various force models), but to maintain and maneuver these configurations, some inertial thrust is required to supplement the nearly propellant-less charge control. In this work, invariant manifold theory is applied to dynamically unstable Coulomb configurations, as part of a generalized procedure to formulate and parameterize optimal transfers from one Coulomb configuration to another. The emphasis is on minimizing the inertial thrust necessary to complete such reconfigurations, in part, by exploiting uncontrolled motion along the manifolds. The possible permutations and variations for modeling the optimal transfers, that are within the scope of the general methodology, are discussed. Numerical results are then provided, as demonstrative examples of the optimization procedure, using a two-craft Coulomb formation model with linearized two-body gravity and simple control parameterizations. Particle Swarm Optimization, a novel stochastic method, is used to solve the optimal transfer problems and its adeptness at doing so, as well as its additional utility in Coulomb formation research, is addressed. [View Full Paper]

AAS 12 – 105

Effective Coulomb Force Modeling in a Space Environment

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

Coulomb formation flight is an emerging concept that utilizes electrostatic forces to maintain a formation of close proximity spacecraft. This paper uses analytic models and numerical simulations to explore the extent of plasma environment shielding on Coulomb forces with large potentials relative to the ambient plasma energy. The use of effective Debye lengths are used in analytic models to approximately and numerically efficiently calculate the force between charged objects. This is computed specifically for Coulomb free-flying formations and tethered Coulomb structures with nodal separations at dozens of meters operating in the geosynchronous plasma environment. It is shown that the force between a sphere and point charge is accurately captured with the effective Debye length, as opposed to the classic Debye length solutions that have errors exceeding 50%. One notable finding is that the effective Debye lengths in low earth orbit plasmas about a charged body are increased from the centimeter to meter level. This is a promising outcome, as the reduced shielding provides sufficient force levels for operating the electrostatically inflated membrane structures concept at these dense plasma altitudes. [View Full Paper]

AAS 12 – 106

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

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

The use of electrostatic (Coulomb) actuation for formation flying is attractive because non-renewable fuel reserves are not depleted and plume impingement issues are avoided. Prior analytical electrostatic force models used for Coulomb formations assume spherical spacecraft shapes, which include mutual capacitance and induced effects. However, this framework does not capture any orientation dependent forces or torques on generic spacecraft geometries encountered during very close operations and docking scenarios. The Multi Sphere Model (MSM) uses a collection of finite spheres to represent a complex shape and analytically approximate the Coulomb interaction with other charged bodies. Finite element analysis software is used as a truth model to determine the optimal MSM parameters. The model is robust to varying system parameters such as prescribed voltages and external shape size. Using the MSM, faster-than-realtime electrostatic simulation of six degree of freedom relative spacecraft motion is feasible, which is crucial for the development of robust relative position and orientation control algorithms in local space situational awareness applications.
[View Full Paper]

AAS 12 – 107

Analysis on Spacecraft Formation Flying in Elliptic Reference Orbits

Jonghee Bae and **Youdan Kim**, School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, South Korea

Formation analysis is performed for the periodic relative motion between two spacecraft in Keplerian elliptic orbits. While the relative motion in the circular reference orbit has an ellipse in the radial/along-track plane, the follower spacecraft in the elliptical orbit does not have an ellipse of fixed eccentricity due to the eccentricity of the reference orbit. In this study, the spacecraft formation flying is analyzed to describe the natural periodic relative motion. The instantaneous eccentricity of the relative motion is derived in the radial/along-track plane formation and the along-track/cross-track plane formation. As a result, the desired constraints are provided for the formation design. Numerical simulations are performed to provide the periodic relative motion and the formation trajectories in the elliptical reference orbit. The variation of the formation radius according to the eccentricity of the reference orbit is analyzed. [View Full Paper]

AAS 12 – 108

Comparison and Application Analysis of Classical Relative Motion Models

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

In this paper several classical relative motion models are compared for a wide variety of conditions. The accuracy and applicability of these models are analyzed. The models involved in this investigation are the familiar Hill's equations, Lawden's equations, Alfriend's geometric method, a new model based on a new set of relative orbit elements and a numerical propagator. The effects of variations of orbital parameters, orbit types, the relative-orbital size and the reference orbit eccentricity are analyzed. The four relative model's capability of formation design is also researched. The proposed method and conclusions are validated through numerical examples. [View Full Paper]

SESSION 2: SPACE SITUATIONAL AWARENESS
Chair: John Seago, Analytical Graphics, Inc.

AAS 12 – 109
(Paper Withdrawn)

AAS 12 – 110

Delta-V Distance Object Correlation and Maneuver Detection with Dynamics Parameter Uncertainty and Generalized Constraints

Marcus J. Holzinger and **Kyle T. Alfriend**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.; **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

Correlating observations with one another or with known objects as well as detecting and characterizing maneuvers is examined. A survey of existing observation correlation and maneuver detection techniques is given, and potential shortcomings for maneuvering spacecraft identified. Existing optimal control correlation and maneuver detection methods are extended to accommodate arbitrary general intermediate state constraints and associated distributions, as well as dynamics parameter uncertainty. Simulated results are reviewed, and conclusions and future work are outlined. [View Full Paper]

AAS 12 – 111

Utilizing Stability Metrics to Aid in Sensor Network Management Solutions for Satellite Tracking Problems

Patrick S. Williams and **David B. Spencer**, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.;
Richard S. Erwin, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

This paper examines techniques for measuring the stability of both the state-space dynamics and uncertainty propagation of space objects within a multi-object, multi-sensor satellite tracking problem. These measurements of stability are quantified through the calculation of various Lyapunov exponents, and applied as (or within) a utility metric to create sensor schedules dictating when a particular sensor should observe a particular object. It is the goal of these schedules to reduce the total uncertainty of all objects tracked, a process that is inherently coupled with the object's state-uncertainty estimation, handled through the application of a nonlinear filter. These methods of scheduling (also known as sensor tasking) and nonlinear filtering are applied to a simulation which attempts to represent a simplified tracking component of the Space Situational Awareness problem. As a primary objective, results from simulations utilizing these stability measures are compared to a more traditional information-theoretic based tasking approach utilizing Shannon information gain. As a secondary objective two nonlinear filters, an extended Kalman filter and unscented Kalman filter, are studied to see the effect of estimator selection on sensor scheduling based on these various tasking methods.
[View Full Paper]

AAS 12 – 112

Comparison of Two Single-Step, Myopic Sensor Management Decision Processes Applied to Space Situational Awareness

Patrick S. Williams and **David B. Spencer**, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.;
Richard S. Erwin, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

This paper describes a sensor tasking, or sensor network management approach for a multiobject, multi-sensor tracking problem analogous to the monitoring of resident space objects known as Space Situational Awareness (SSA). In the SSA problem large discrepancies between satellites tracked and resources available to track them create difficulties in maintaining accurate satellite position and uncertainty estimates. Long periods of either inability to make observations (due to line-of-sight access) or unavailability of sensors (due to scheduling constraints) necessitates the need to intelligently determine which satellites should be observed and which should be ignored at various times, a process known as sensor tasking. To conduct this tasking, two information theory-based utility metrics are used, where one is a measure of absolute information gain and the other a quantification of relative information gain. These metrics are implemented in a single-step optimization problem in order to maximize total information gained over a series of observations from five sensors (four ground-based, one orbiting) measuring the range and azimuth of several satellites. Using a simple simulation of the estimation and tasking components of the SSA problem, these metrics are implemented in conjunction with an extended Kalman filter or unscented Kalman filter to obtain the satellites state and uncertainty estimates. Comparisons are made between the two methods of tasking and two estimators in order to determine which combinations of filters/tasking produce the most desirable tracking performance. [View Full Paper]

AAS 12 – 113
Co-Orbiting Anti-Satellite Vulnerability

Salvatore Alfano, Center for Space Standards and Innovation (CSSI), Colorado Springs, Colorado, U.S.A.

This work uses simple orbital dynamics to initially assess the vulnerability of a satellite to a Space-Based Interceptor (SBI) launched from an orbiting, anti-satellite, carrier platform. The method produces an engagement volume derived from the position and velocity vectors of the launching platform, the range of impulsive velocities that can be imparted to the SBI upon deployment, and the maximum expected time-of-flight from release until intercept. To accommodate the carrier's orbital eccentricity, a sufficient number of cases must be examined at various release points (perigee, apogee, and intermediate true anomalies) to capture the complete range of possible intercepts, thus making the vulnerability volume slightly larger than it might otherwise be for a specific release. The results are shown as points in space contained within a convex hull or minimum volume enclosing ellipsoid and are displayed relative to the orbiting carrier platform. If a particular satellite is predicted to pass through the volume then it is considered vulnerable although the SBI would have been launched much earlier. This method provides the initial tools needed to predict a family of on-orbit engagements for a prespecified SBI. [View Full Paper]

AAS 12 – 114
(Paper Withdrawn)

AAS 12 – 115

Inverse Problem Formulation Coupled with Unscented Kalman Filtering for State and Shape Estimation of Space Objects

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

This work addresses issues related to resolving space objects i.e. Space Situational Awareness (SSA). The motivation behind this paper is to further current techniques used to estimate states associated with non-resolved space objects. Furthermore, this work deals with an inverse problem for a system of nonlinear stochastic differential equations. This system of equations corresponds to the two body orbit equations along with models accounting for effects of atmospheric drag, solar radiation pressure, and Earth's aspherical shape. The present work implements an Unscented Kalman filter (UKF) in conjunction with a batch estimation loop. The UKF estimates the states and parameters of the resident space object (RSO) until a pre-determined measurement batch size criterion is met. The estimates are then passed to the batch loop where a cost function is minimized to improve the estimates of the RSO's parameters further. The batch loop is implemented using two methods; the first uses the Levenberg-Marquardt technique while the second uses a Gauss-Newton algorithm. Moreover, two experiments are conducted. The first experiment uses the traditional UKF implementation and is treated as the benchmark for the implementation of the batch loop. The second experiment uses the UKF along with the batch loop. The implementation of the batch loop shows a slight improvement over the traditional UKF implementation.
[View Full Paper]

AAS 12 – 116

(Paper Withdrawn)

AAS 12 – 117

Inactive Space Object Shape Estimation Via Astrometric and Photometric Data Fusion

Richard Linares and **John L. Crassidis**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.; **Moriba K. Jah**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

This paper presents a method to determine the shape of a space object in orbit while simultaneously recovering the observed space object's inertial orientation and trajectory. This work studies a shape estimation approach based on octant triangulation applied to light curve and angles data fusion. The filter employs the Unscented estimation approach, reducing passively-collected electro-optical data to infer the unknown state vector comprised of the space object inertial-to-body orientation, position and their respective temporal rates. Recovering these characteristics and trajectories with sufficient accuracy is shown in this paper. The performance of this strategy is demonstrated via simulated scenarios. [View Full Paper]

SESSION 3: ATTITUDE DETERMINATION
Chair: Dr. Sergei Tanygin, Analytical Graphics, Inc.

AAS 12 – 118
Filtering Solution to Relative Attitude Determination Problem Using Multiple Constraints

Richard Linares and **John L. Crassidis**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.; **Yang Cheng**, Department of Aerospace Engineering, Mississippi State University, Mississippi State, Mississippi, U.S.A.

In this paper a filtering solution for the relative attitude and relative position of a formation of two spacecraft with multiple constraints is shown. The solution for the relative attitude and position between the two spacecraft is obtained only using line-of-sight measurements between them and a common (unknown) object observed by both spacecraft. The constraint used in the solution is a triangle constraint on the vector observations. This approach is extended to multiple objects by applying this constraint for each common object. Simulation runs to study the performance of the approach are shown. [View Full Paper]

AAS 12 – 119
Complete Closed Form Solution of a Tumbling Triaxial Satellite Under Gravity-Gradient Torque

Martin Lara and **Sebastián Ferrer**, Grupo de Dinámica Espacial, Universidad de Murcia, Spain

The attitude dynamics of a tumbling triaxial satellite under gravity-gradient is revisited. The total reduction of the Euler-Poinsot Hamiltonian provides a suitable set of canonical variables that expedites the perturbation approach. Two canonical transformations reduce the perturbed problem to its secular terms. The secular Hamiltonian and the transformation equations of the averaging are computed in closed form of the triaxiality coefficient, thus being valid for any triaxial body. The solution depends on Jacobi elliptic functions and integrals, and applies to non-resonant rotations under the assumption that the tumbling rate is much higher than the orbital or precessional motion.
[View Full Paper]

AAS 12 – 120

Cayley Attitude Technique

John E. Hurtado, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

Single point attitude determination is the problem of estimating the instantaneous attitude of a rigid body from a collection of vector observations taken at a single moment in time. Many methods have been proposed to solve this problem, most of which are based on Wahba's problem. Here, a new technique is presented that uses a generalized Cayley transform. Algorithms to optimally solve the attitude estimation problem for a wide family of attitude parameters are given. [View Full Paper]

AAS 12 – 121

Attitude Estimation in Higher Dimensions

John E. Hurtado, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

To date, there has been only one archival journal paper devoted to attitude determination in dimensions higher than three. A review of literature reveals, however, that the kinematics, kinetics, and control of bodies that occupy abstract higher dimensional spaces has been extensively investigated. Many of those studies tell of a relevant connection between real physical systems in three dimensions and a counterpart in higher dimensions. Therefore, it is with similar hopes in mind that the problem of single instance attitude estimation for bodies in abstract higher dimensional spaces is reviewed. [View Full Paper]

AAS 12 – 122

Linear Solutions to Single Instance Position and Attitude Estimation

John E. Hurtado, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

The combined attitude and position estimation problem has received less attention than the attitude only problem. Here, new developments are presented for this problem that use a generalized Cayley transform. One interesting viewpoint involves casting the position and attitude in three dimensions as an attitude-only problem in four dimensions. [View Full Paper]

AAS 12 – 123

Analysis and Comparison of Rate Estimaton Algorithms Using Coarse Sun Sensors and a Three Axis Magnetometer

Tae W. Lim, Aerospace Engineering Department, United States Naval Academy, Annapolis, Maryland, U.S.A.; **Frederick A. Tasker**, U.S. Naval Research Laboratory, Washington D.C., U.S.A.

This paper examines various rate estimation approaches using sun vector and earth magnetic field B-vector measurements, either individually or collaboratively, primarily for safehold design applications. Approaches of estimating body rates using coarse sun sensors (CSS's) and a three axis magnetometer (TAM) are presented in detail including sun vector only (or CSS only) approach, magnetic field vector only (or TAM only) approach, and combined sun vector and magnetic field vector approaches. Using simulations and flight operations experiences the paper discusses their advantages and disadvantages to help design a safehold mode that will meet the design requirements most effectively. [View Full Paper]

AAS 12 – 124

Autonomous 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.

This paper investigates the use of relative attitude sharing between two spacecraft. The first, sharing, spacecraft, has an inertial attitude sensor. The second, receiving, spacecraft lacks an attitude sensor. The sharing spacecraft is able to sense relative attitude, enabling determination of the inertial attitude of the receiving spacecraft composed with the inertial attitude of the sharing spacecraft. Relative attitude is assumed to be available only under certain alignment conditions consistent with proper orientation of a passive relative attitude sensor on the sharing spacecraft and attitude fiducials on the receiving spacecraft. It is shown that an uncertainty-based metric derived from the Extended Kalman Filter can be used to autonomously determine when the spacecraft should modify their pointing objectives to accommodate resource sharing. This uncertainty-based decision parameter enables the spacecraft to share information more efficiently than a fixed-measurement update schedule, by switching the tracking objective from a target mode to a sharing mode, only when needed. It is shown that a star tracker, or equivalent attitude determination system on the sharing spacecraft can accommodate the attitude measurement requirements of multiple spacecraft. [View Full Paper]

AAS 12 – 125

Novel Multiplicative Unscented Kalman Filter for Attitude Estimation

Renato Zanetti, Vehicle Dynamics and Control, The Charles Stark Draper Laboratory, Houston, Texas, U.S.A.; **Kyle J. DeMars**, National Research Council (NRC) Postdoctoral Research Fellow, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.;
Daniele Mortari, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

A novel spacecraft attitude estimation algorithm is presented. The new algorithm utilizes unit vector measurements and is based on the unscented Kalman filter (UKF). The UKF, like the extended Kalman filter, employs a linear update in which an additive residual is formed. The residual is given by the difference between the measurement and its mean. This work utilizes a multiplicative residual in which the measurement and the mean are multiplied together using the vector cross product. Because of the nature of the problem, a multiplicative residual combined with a multiplicative update is a more natural solution. [View Full Paper]

AAS 12 – 126

Projective Geometry of Attitude Parameterizations with Applications to Control and Tracking

Sergei Tanygin, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

Vectorial attitude parameterizations, defined as products of the unit axis of rotation and various functions of the rotation angle, can be viewed as projections from the unit quaternion hypersphere onto a hyperplane tangential to the hypersphere at a point representing zero rotation. It is shown that, if the projection hyperplane is moved to any other point on the hypersphere, the resulting parameterization and its kinematics follow directly from the formulations that are well-known in attitude tracking problems. It is also shown how a perspective projection geometry that can support both tangent and sine families of attitude parameters can be configured to efficiently and accurately approximate the rotation vector parameterization for a full range of rotation angles. This approximation is used to efficiently improve linearity of closed-loop attitude dynamics resulting from feedback control laws. [View Full Paper]

SESSION 4: ASTERIOD AND NEAR-EARTH OBJECT MISSIONS I
Chair: Kenneth Williams, KinetX, Inc.

AAS 12 – 127
Earth Delivery of a Small NEO with an Ion Beam Shepherd

Claudio Bombardelli, **Hodei Urrutxua** and **Jesús Peláez**, Space Dynamics Group, Technical University of Madrid (UPM), Spain

The possibility of capturing a small Near Earth Asteroid (NEA) and delivering it to the vicinity of the Earth has been recently explored by different authors. The key advantage would be to allow a cheap and quick access to the NEA for science, resource utilization and other purposes. Among the different challenges related to this operation stands the difficulty of robotically capturing the object, whose composition and dynamical state could be problematic. In order to simplify the capture operation we propose the use of a collimated ion beam ejected from a hovering spacecraft in order to maneuver the object without direct physical contact. The feasibility of a possible asteroid retrieval mission is evaluated. [View Full Paper]

AAS 12 – 128
Conceptual Design and Analysis of Planetary Defense Technology (PDT) Demonstration Missions

George Vardaxis, **Alan Pitz** and **Bong Wie**, Asteroid Deflection Research Center, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

When the warning time of the impact threat of a near-Earth object (NEO) is short, the use of nuclear explosives may become necessary to safeguard the Earth. A variety of nuclear options, such as standoff, surface contact, and subsurface explosions, for mitigating the impact threats of NEOs have been proposed and studied in the past two decades. Eventually in the near future, an actual flight demonstration mission may become necessary to verify and validate the overall effectiveness and robustness of such various nuclear options and the associated space technologies. This paper presents the conceptual mission architecture design of such flight validation missions with a consideration of three mission cost classifications (e.g., $500M, $1B, and $1.5B). [View Full Paper]

AAS 12 – 129

Design of Spacecraft Missions to Test Kinetic Impact for Asteroid Deflection

Sonia Hernandez, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.; **Brent W. Barbee**, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Earth has previously been struck with devastating force by near-Earth asteroids (NEAs) and will be struck again. Telescopic search programs aim to provide advance warning of such an impact, but no techniques or systems have yet been tested for deflecting an incoming NEA. To begin addressing this problem, we have analyzed the more than 8000 currently known NEAs to identify those that offer opportunities for safe and meaningful near-term tests of the proposed kinetic impact asteroid deflection technique. In this paper we present our methodology and results, including complete mission designs for the best kinetic impactor test mission opportunities. [View Full Paper]

AAS 12 – 130

Feedback Stabilization of Displaced Periodic Orbits: Application to Binary Asteroid

Jules Simo and **Colin R. McInnes**, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, United Kingdom

This paper investigates displaced periodic orbits at linear order in the circular restricted Earth-Moon system (CRTBP), where the third massless body utilizes a hybrid of solar sail and a solar electric propulsion (SEP). A feedback linearization control scheme is implemented to perform stabilization and trajectory tracking for the nonlinear system. Attention is now directed to binary asteroid systems as an application of the restricted problem. The idea of combining a solar sail with an SEP auxiliary system to obtain a hybrid sail system is important especially due to the challenges of performing complex trajectories. [View Full Paper]

AAS 12 – 131

Dynamical Characterization of 1:1 Resonance Crossing Trajectories at Vesta

Àlex Haro, Departament de Matemàtica Aplicada i Anàlisi, Universitat de Barcelona; Barcelona, Spain; **Josep-Maria Mondelo**, Departament de Matemàtiques, IEEC & Universitat Autònoma de Barcelona, Bellaterra (Barcelona), Spain; **Benjamin F. Villac**, Department of Mechanical and Aerospace Engineering, University of California, Irvine, California, U.S.A.

Motivated by the challenges associated with the 30-days transfer of the 1:1 resonance crossing of the Dawn mission, which entered its High–Altitude Mapping Orbit on Sept. 29, 2011, this paper analyzes the dynamical structure and sensitivity of 1:1 resonance crossing ballistic transfers at Vesta. In particular, a representation of the set of transit orbits that respects the associated center manifold structures is presented. This allows for the characterization of the extrema of various properties, such as minimum ballistic resonance crossing time. A further exploration using chaoticity maps reveal the likely existence of homoclinic phenomena and connections with furhter resonances as the energy is increased. [View Full Paper]

AAS 12 – 132

Close Proximity Asteroid Operations Using Sliding Control Modes

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.; **Julie Bellerose**, Carnegie Mellon University SV / NASA ARC, NASA Ames Research Center, Moffet Field, California, U.S.A.

Due to their uncertain dynamical environment, close proximity operations around small celestial bodies are extremely challenging. In this paper, we show that the Multiple Sliding Surface Guidance (MSSG) algorithm, already proposed for autonomous asteroid pin-point guidance, can be extended to guide the transition of the spacecraft from any two desired states, including hovering, surface and orbital states. MSSG is based on Higher Order Sliding Mode (HOSM) control theory and takes advantage of the fact that the motion of the spacecraft around asteroids exists in a 2-sliding mode, i.e. the acceleration command appears at the second derivative of the defined sliding surface. The proposed algorithm is constructed by the proper concatenation of two sliding surfaces and takes advantage of the system's ability to reach the sliding surfaces in finite time. Importantly, the MSSG algorithm does not require either ground-based or on-board trajectory generation but computes an acceleration command that targets a specified state based on purely knowledge of the current and desired position and velocity. The classes of trajectories generated in this fashion are a function of the current and final states as well as of the guidance gains. Moreover, the controller is shown to be globally stable in the Lyapunov sense. MSSG is implemented in simulation scenarios comprising a variety of operations around a model asteroid, demonstrating the ability of the algorithm to guide the system between 1) two hovering states, 2) surface and hovering states and 3) surface to hovering. The MSSG algorithm is also shown to be able to shape the closed-loop trajectories to satisfy the requirements imposed by the need to execute a defined set of close-proximity operations. [View Full Paper]

AAS 12 – 133

Fourth-Order Gravity Gradient Torque of Spacecraft Orbiting Asteroids

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

The dynamical behavior of spacecraft around asteroids is a key element in design of such missions. An asteroid's irregular shape, non-spherical mass distribution and its rotational state make the dynamics of spacecraft quite complex. This paper focuses on the gravity gradient torque of spacecraft around nonspherical asteroids. The gravity field of the asteroid is approximated as a 2nd degree and order-gravity field with harmonic coefficients C_{20} and C_{22}. By introducing the spacecraft's higher-order inertia integrals, a full fourth-order gravity gradient torque model of the spacecraft is established through the gravitational potential derivatives. Our full fourth-order model is more precise than previous fourth-order model due to the consideration of higher-order inertia integrals of the spacecraft. Some interesting conclusions about the gravity gradient torque model are reached. Then a numerical simulation is carried out to verify our model. In the numerical simulation, a special spacecraft consisted of 36 point masses connected by rigid massless rods is considered. We assume that the asteroid is in a uniform rotation around its maximum-moment principal axis, and the spacecraft is on the stationary orbit in the equatorial plane. Simulation results show that the motion of previous fourth-order model is quite different from the exact motion, while our full fourth-order model fits the exact motion very well. And our model is precise enough for practical applications. [View Full Paper]

AAS 12 – 134

On the Planar Motion in the Full Two-Body Problem

Pamela Woo and **Arun K. Misra**, Department of Mechanical Engineering, McGill University, Montreal, Canada; **Mehdi Keshmiri**, Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran

The motion of binary asteroids, modeled as the full two-body problem, is studied, considering shape and mass distribution of the bodies. Using the Lagrangian approach, the equations governing the planar motion are derived. The resulting system of four equations is nonlinear and coupled. These equations are solved numerically. In the particular case where the bodies are axisymmetric around an axis normal to the plane, the system reduces to a single equation, with small nonlinearity. The method of multiple scales is used to obtain a first-order solution for the reduced nonlinear equation. This is shown to be sufficient when compared with the numerical solution. Example cases include peanut-shaped bodies. [View Full Paper]

SESSION 5: DYNAMICAL SYSTEMS THEORY I
Chair: Dr. Robert Melton, Pennsylvania State University

AAS 12 – 135
Invariant Manifolds to Design Scientific Operative Orbits in the Pluto-Charon Binary System

Davide Guzzetti, **Michèle Lavagna** and **Roberto Armellin**, Department of Aerospace Engineering, Politecnico di Milano, Milan, Italy

Feasibility of operative orbits in the Pluto-Charon system has been investigated in this work. Given that currently only the New Horizon NASA mission will perform a quick fly-by of Pluto-Charon, the chance to close a spacecraft in orbit around the system would represent a significant add-on in the science knowledge domain and an interesting challenge from the flight dynamics perspective. A R3BP coupled with the invariant manifolds are the main tools here exploited to manage the trajectories design; possible itineraries and strategies, that can meet the requirements of costs minimization, long operative life and adequate coverage of the surfaces, are proposed. [View Full Paper]

AAS 12 – 136
Approaching Moons from Resonance Via Invariant Manifolds

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

In this work, the approach phase from the final resonance of the endgame scenario in a tour design is examined within the context of invariant manifolds. Previous analyses have typically solved this problem either by using numerical techniques or by computing a catalog of suitable trajectories. The invariant manifolds of a selected set of libration orbits and unstable resonant orbits are computed here to serve as guides for desirable approach trajectories. The analysis focuses on designing an approach phase that may be tied into the final resonance in the endgame sequence while also targeting desired conditions at the moon. [View Full Paper]

AAS 12 – 137

Attainable Sets in Space Mission Design: A Method to Define Low-Thrust, Invariant Manifold Trajectories

G. Mingotti, Distributed Space Systems Lab, Faculty of Aerospace Engineering, Technion–Israel Institute of Technology, Haifa, Israel; **F. Topputo** and **F. Bernelli-Zazzera**, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Milano, Italy

A method to incorporate low-thrust propulsion into the invariant manifolds technique for space trajectory design is presented in this paper. Low-thrust propulsion is introduced by means of attainable sets that are used in conjunction with invariant manifolds to define first guess solutions in the restricted-three body problem. They are optimized in the restricted four-body problem where an optimal control problem is formalized. Several missions are investigated in the Earth–Moon system: transfers to libration point orbits and to periodic orbits around the Moon. Attainable sets allow the immediate design of efficient complex space trajectories. [View Full Paper]

AAS 12 – 138

Efficient Trajectory Correction for L2 Halo-Orbit Transfer Using Stable Manifolds

Yoshihide Sugimoto and **Triwanto Simanjuntak**, Department of Space and Astronautical Science, The Graduate University for Advanced Studies, Yoshinodai, Sagamihara, Japan; **Masaki Nakamiya** and **Yasuhiro Kawakatsu**, Department of Space Systems and Astronautics, Institute of Space and Astronautics Science, Yoshinodai, Sagamihara, Japan

This study investigates the effective method to correct the transfer trajectory into the Halo-orbit by using the stable manifolds. The Halo-orbits around collinear Lagrange points are recently in the spotlight because of its periodicity, large field of view to the deep-space, and stable thermal environment. Japan Aerospace Exploration Agency (JAXA) is currently planning the first Japanese astronomical mission putted into the Halo-orbit named Space Infrared telescope for Cosmology and Astrophysics (SPICA). SPICA is designed to utilize the stable manifolds to transfer into the Halo-orbit. The stable manifolds, which are constructed by dynamical system theory (DST), are the strong feature to insert the spacecraft naturally into Halo-orbit. In this paper, we want to show the stable manifolds prediction using scaling method at first and efficient trajectory correction method by means of predicted stable manifolds in the Circular Restricted Three-Body Problem (CR3BP). [View Full Paper]

AAS 12 – 139

Discrete-Time Bilinear Representation of Continuous-Time Bilinear State-Space Models

Minh Q. Phan, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, U.S.A.; **Yunde Shi**, **Raimondo Betti** and **Richard W. Longman**, Columbia University, New York, New York, U.S.A.

This paper develops techniques to represent a first-order continuous-time bilinear state-space model by various first-order discrete-time bilinear state-space models. Although it is always possible to discretize any well-behaved continuous-time model, of interest are techniques that keep the discrete-time models in first-order form while maintaining the simple bilinear structure of the original continuous-time model for control and estimation applications. Adams-Bashforth integration methods are found to meet these requirements, whereas simpler Euler methods produce unstable discrete-time models, and other methods do not produce models in bilinear form. [View Full Paper]

AAS 12 – 140

Expanding Transfer Representations in Symbolic Dynamics for Automated Trajectory Design

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

Previous studies have shown symbolic dynamics can be used to find transfers with desirable global transit characteristics using libration point region and manifold structures in the CR3BP. However, this method cannot control for practical orbital elements such as altitude and inclination. Extensions of existing symbolic dynamic methods are needed for automated selection of trajectories with these attributes. Enabling this are recent studies which have shown connections between important classical characteristics and structures such as resonant orbits, collision trajectories, and manifolds. This paper analyzes the utility of such an extension in the planar problem as a first step in this direction. [View Full Paper]

AAS 12 – 141
(Paper Withdrawn)

AAS 12 – 142

A Theory of Low Eccentricity Earth Satellite Motion

William E. Wiesel, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright Patterson AFB, Ohio, U.S.A.

Earth satellite motion is considered from the point of view of periodic orbits and Floquet theory in the earth's zonal potential field. Periodic orbits in the zonal potential are nearly circular, except near the critical inclination. The local linear solution near the periodic orbit includes two degenerate modes that locally mirror the global invariance to time and nodal rotation, at least in the zonal potential. Since the earth's oblateness is included in the periodic orbit, perturbations generally begin at one part in 10^5, not one part in 10^3. Perturbations to the periodic orbit are calculated for sectoral and tesseral potential terms, for air drag, and for third body effects. The one free oscillatory mode of the periodic orbit is the eccentricity / argument of perigee analogues, and this can be extended past the first order in small quantities. There results a compact, purely numerical set of algorithms that may rival numerical integration in their accuracy, but have the usual "general perturbations" advantage of calculation directly at the time of interest, without having to perform a long propagation. [View Full Paper]

AAS 12 – 143

Two-Point Boundary Value Problem of the Relative Motion

Hao Zhang, **Yu-shan Zhao**, **Peng Shi** and **Bao-jun Li**, School of Astronautics, Beihang University, Beijing, China

The two-point boundary value problem of the relative motion is studied, in which the chief spacecraft's motion is known and the motion of the deputy spacecraft should be determined. An accurate numerical solution to this problem is reviewed. Then two types of linearized analytical solutions, one based on linearization of a reference Lambert's problem of the chief and the other based on relative motion's state transition matrix, are derived. These two linearized solutions are shown to be equivalent. Meanwhile, both solutions suffer from singularity, resulting in huge fuel consumption under certain circumstances. The reason of the singularity is analyzed and some analytical expression relations are given when the chief's orbit is a circle. In the end, methods to check and alleviate this singularity are presented. Several examples are also given to demonstrate the findings. [View Full Paper]

SESSION 6: FORMATION FLYING II
Chair: Dr. Matthew Wilkins, Schafer Corporation

AAS 12 – 144
Circular Lattice String-of-Pearls Constellations for Radio Occultation Mission

Sanghyun Lee and **Daniele Mortari**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

This paper addresses the problem of designing suitable satellite constellation for Radio Occultation mission. Radio occultation for the Earth atmosphere usually requires global coverage and short interval measurements. The Circular (2-D) Lattice Flower Constellations theory is here applied to design constellations maximizing active time with providing global coverage and frequent measurements. Optimizations are performed using Genetic Algorithms to estimate constellation design parameters. Optimization is constrained by altitude range (drag and Van Allen belt avoidance) and nodal precession is used to obtain global coverage. The resulting constellation geometries have been explored from a coverage performance perspective. Two coverage estimation methods have been used to evaluate coverage performance. The performance of some solutions are provided to help optimality selection. [View Full Paper]

AAS 12 – 145
Common-Period Four-Satellite Continuous Global Coverage Constellations Revisited

John E. Draim, Satellite Constellation Design, Launch Vehicles, and Floating Launch Rocket Design and Operations, Vienna, Virginia, U.S.A.; **Weijung Huang**, Department of Mechanical and Aerospace Engineering, University of Missouri-Columbia, Columbia, Missouri, U.S.A.; **David A. Vallado** and **David Finkleman**, Center for Space Standards and Innovation, Analytical Graphics Inc., Colorado Springs, Colorado, U.S.A.; **Paul J. Cefola**, Department of Mechanical and Aerospace Engineering, University at Buffalo (SUNY), Amherst, New York, U.S.A.

Global constellation coverage has been a topic of interest for many years. The Draim four-satellite continuous global coverage constellation offers improvement over traditional coverage constellations. We re-look at this constellation using new analytical search techniques, computational methods to assess the dynamic performance, and graphical depictions. Using the original orbits, we vary orbital parameters to determine how the constellation reacts to additional constraints. Evaluation criteria are expanded to include the number of satellites, distance from the earth, orbital regimes, conjunction probabilities, communication link margins, etc. Technical statistics of satellite access parameters and graphical depictions are also examined. [View Full Paper]

AAS 12 – 146

Optimization of Hybrid Orbit Constellation Design for Space-Based Surveillance System

Hongzheng Cui, **Xiucong Sun** and **Chao Han**, School of Astronautics, Beihang University, Beijing, China; **Geshi Tang**, Flight Dynamics Laboratory, Beijing Aerospace Control Center, Beijing, China

The focus for this paper is to design the satellite constellation to observe GEO regime, and HEO and SubGEO are adopted as mission orbits for Space-Based Surveillance System (SBSS). A new method called the rapid method for satellite constellation performance calculation is developed by the Hermite interpolation technique to reduce the computing complication and time. The SBSS constellation optimization models are presented and the evolutionary algorithm is adopted to optimize the configuration parameters. [View Full Paper]

AAS 12 – 147

Reducing Walker, Flower, and Streets-of-Coverage Constellations to a Single Constellation Design Framework

Jeremy J. Davis, VectorNav Technologies LLC, Richardson, Texas, U.S.A.;
Daniele Mortari, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

Satellite constellations are typically designed using either Walker or streets-of-coverage methods. In some cases, the constellation may be optimized on the individual satellite level to produce non-uniform distributions. The recently developed lattice theory of Flower Constellations has generalized Walker constellations but cannot accommodate non-uniformity or streets-of-coverage. By inverting the integer lattice, one can define three continuous variables that generalize Flower and streets-of-coverage constellations while permitting non-uniform designs. Transitioning from integer parameters to continuous ones increases computational complexity but provides greater design flexibility and optimization. The highly non-uniform GPS constellation and the Iridium global communications constellation are both studied using the new framework.
[View Full Paper]

AAS 12 – 148

Perturbation Effects on Elliptical Relative Motion Based on Relative Orbit Elements

Jianfeng Yin and **Chao Han**, School of Astronautics, Beihang University, Beijing, China; **Geshi Tang**, Flight Dynamics Laboratory, Beijing Aerospace Control Center, Beijing, China

A new elliptical relative motion model with no singularity problem is derived based on the relative orbit elements. The inverse transformation of state transfer matrix is obtained to analyze perturbation effects and control strategy. The velocity impulse control laws, including out-of-plane and in-plane control, are also proposed. Mean orbit elements theory are introduced into the new dynamic model to analyze the perturbation effects, mainly J2. The effects of gravitational perturbations are simulated and analyzed using the proposed feedback control method. The simulations presented clearly show that the new relative motion model could describe dynamics of formation flying more efficiently. [View Full Paper]

AAS 12 – 149

Review of the Solutions to the Tschauner-Hempel Equations 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 Tschauner-Hempel equations model the motion of a deputy satellite relative to a chief satellite with arbitrary eccentricity. They are linear non-autonomous differential equations with the chief's true anomaly as the independent variable. Since they first appeared, numerous analytical solutions have been presented. This paper provides a focused review of some of these solutions: highlighting how they are related and their singularities. The fundamental solutions of the Tschauner-Hempel equations can be interpreted geometrically as generalizations of the drifting two-by-one ellipse that describes relative motion in circular orbits. General solutions are formed by taking linear combinations of these fundamental solutions. [View Full Paper]

AAS 12 – 150
(Paper Withdrawn)

AAS 12 – 151

Stability Analysis and Out-of-Plane Control of Collinear Spinning Three-Craft Coulomb Formations

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

This paper analyzes the effects of out-of-plane perturbations on planar motion for collinear three-craft Coulomb formations with set charges. The formation is assumed to be spinning in deep space without relevant gravitational forces present. Previous work analytically proves marginal stability assuming in-plane motion with circular relative trajectories and the initial position and velocity perturbations confined to the orbital plane. In this paper, a new derivation of the equations of motion in cylindrical coordinates is produced to analyze the out-of-plane motion in more detail. The out-of-plane motion is shown to decouple to first order from the marginally stable in-plane motion. A control law is developed to maintain the out-of-plane motion within specified deadbands. For small relative out-of-plane perturbations, the control law succeeds in preserving the in-plane variant shape despite some out-of-plane motion. A trend between the settling time and deadband, which defines the largest out-of-plane errors allowed before the controller is turned on, is determined which illustrates how large the deadband may be before the in-plane motion is affected. A Monte-Carlo analysis also indicates that the spin-rate and formation size do not have a significant influence on the out-of-plane instability of a collinear invariant shape Coulomb formation.
[View Full Paper]

AAS 12 – 152

Velocity Extrema in Spacecraft Formation Flight

Shawn E. Allgeier, Schafer Corporation, Albuquerque, New Mexico, U.S.A.;
R. Scott Erwin, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.; **Norman G. Fitz-Coy**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.

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

SESSION 7: OPTIMAL CONTROL
Chair: Dr. Marcus Holzinger, Texas A&M University

AAS 12 – 153
Necessary Conditions for Optimal Impulsive Rendezvous in a Newtonian Gravitational Field

Thomas Carter, Department of Mathematics, Eastern Connecticut State University, Willimantic, Connecticut, U.S.A.; **Mayer Humi**, Department of Mathematical Sciences, Worcester Polytechnic Institute, Worcester, Massachusetts, U.S.A.

The problem of planar optimal impulsive rendezvous with fixed end conditions in a Newtonian gravitational field is approached through a transformation of variables that was recently used by the authors to successfully investigate the problem of optimal impulsive rendezvous near circular orbit. New necessary conditions for solution of this more general problem are presented in terms of these transformed variables.
[View Full Paper]

AAS 12 – 154
Existence and Sufficiency Conditions for Optimal Impulsive Rendezvous in a Newtonian Gravitational Field

Thomas Carter, Department of Mathematics, Eastern Connecticut State University, Willimantic, Connecticut, U.S.A.; **Mayer Humi**, Department of Mathematical Sciences, Worcester Polytechnic Institute, Worcester, Massachusetts, U.S.A.

An investigation of the question of existence of solutions of a planar optimal impulsive rendezvous in a Newtonian gravitational field reveals that if the initial and terminal angular momentum are positive, either a solution exists, or else an approximate solution exists to any degree of accuracy. If the differences in the values of the orbital angle where the velocity increments are applied are not integer multiples of π then an actual solution exists, not an approximate one. Under these conditions, necessary and sufficient conditions for optimality are available. The question of realizability of solutions is discussed. An example is presented of a two-impulse rendezvous between the apogees of two identical ellipses having a common center of attraction but different inclination. This example illustrates existence, approximate solutions, and realizability of solutions. [View Full Paper]

AAS 12 – 155

Modified Chebyshev-Picard Iteration Methods for Station-Keeping of Translunar Halo Orbits

Xiaoli Bai and **John L. Junkins**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

The halo orbits around the Earth-Moon L_2 libration point provide a great candidate orbit for a lunar communication satellite, where the satellite remains above the horizon on the far side of the Moon being visible from the Earth at all times. Such orbits are generally unstable and station-keeping strategies are required to control the satellite to remain close to the reference orbit. A recently developed Modified Chebyshev-Picard Iteration method is used to compute corrective maneuvers at discrete time intervals for station-keeping of halo orbit satellite and several key parameters affecting the mission performance are analyzed through numerical simulations. Compared with previously published results, the presented method provides a computationally efficient station-keeping approach which has a simple control structure that does not require weight turning and most importantly, does not need state transition matrix or gradient information computation. The performance of the presented approach is shown to be comparable with published methods. [View Full Paper]

AAS 12 – 156
(Paper Withdrawn)

AAS 12 – 157
(Paper Withdrawn)

AAS 12 – 158

Optimal Solutions and Guidance for Quasi-Planar Ascent over a Spherical Moon

David G. Hull and **Matthew W. Harris**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas, U.S.A.

With the lunar ascent in mind, the minimum-time trajectory of a constant-thrust rocket transferring from one point to another in the neighborhood of a spherical body is solved in the local vertical local horizontal reference frame. It is also assumed that the transfer is quasi-planar and that the thrust pitch and yaw angles are small. The solution of the resulting two-point boundary value problem involves modified thrust integrals and requires three quadratures and one iteration. Results are presented for the optimal trajectory. A result of this solution is that a variable multiplier can be assumed constant, leading to an analytical solution (without quadrature and without iteration) in terms of the well known thrust integrals. These are new solutions for the constant-thrust, minimum-time transfer problem over a spherical body. Both solutions are tested in a sample and hold guidance scheme. First, the out-of-plane initial conditions are set to zero. The planar results show that both solutions satisfy the final conditions, consume the same mass, and use approximately the same thrust pitch angle history. Second, to test out-of-plane performance, the out-of-plane initial conditions are changed to be non-zero. Results are similar. Because the second solution is analytical, it merits further consideration as an onboard guidance algorithm. It is the best analytical solution to date for quasi-planar ascent over a spherical body. [View Full Paper]

AAS 12 – 159

Space Object Maneuver Detection via a Joint Optimal Control and Multiple Hypothesis Tracking Approach

Navraj Singh, **Joshua T. Horwood** and **Aubrey B. Poore**, Numerica Corporation, Loveland, Colorado, U.S.A.

An optimal control framework is presented as a post-processor to a multiple hypothesis tracker for resolving uncorrelated tracks (UCTs) generated by space object maneuvers. The optimal control framework uses the total velocity increment ΔV as the cost functional to determine feasibility of maneuvers. The method obtains accurate ΔV estimates for connecting two UCTs via fuel-optimal maneuvers. In addition, a method is proposed for treating uncertainty in the UCT states, via the unscented transform, to determine the probability that a maneuver is feasible. The approach is most applicable to routine but unannounced fuel-optimal maneuvers conducted by space objects.
[View Full Paper]

SESSION 8: TRAJECTORY OPTIMIZATION I
Chair: Dr. Anil Rao, University of Florida

AAS 12 – 160
(Paper Withdrawn)

AAS 12 – 161
(Paper Withdrawn)

AAS 12 – 162
Automated Inclusion of V-Infinity Leveraging Maneuvers in Gravity-Assist Flyby Tour Design

Demyan V. Lantukh and **Ryan P. Russell**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.;
Stefano Campagnola, California Institute of Technology, Pasadena, California, U.S.A.

Interplanetary and moon tour missions have benefited from the implementation of leveraging maneuvers that efficiently change spacecraft energy relative to a flyby body. In the current work, these v-infinity leveraging maneuvers are reformulated into a boundary value problem more suitable for broad trajectory searches and for the ephemeris case by using the same boundary conditions as the Lambert problem. A root-solve on a complicated one-dimensional function results from this reformulation. The method allows the inclusion of maneuvers in broad tour design searches using only a few integer parameter additions to the search space, while also keeping the Lambert-based architecture. Unlike existing v-infinity leveraging implementations, the new approach easily incorporates flyby bodies in non-circular or ephemeris model orbits. Furthermore, the approach enables leveraging maneuvers between two different flyby bodies. The well-known bi-elliptic transfers are shown to be special cases of interbody leveraging. Examples of the new formulation's utility are also presented using representative interplanetary and intermoon transfers. [View Full Paper]

AAS 12 – 163
Closed-Form Solutions for Open Orbits around an Oblate Planet

Vladimir Martinusi and **Pini Gurfil**, Distributed Space Systems Lab, Faculty of Aerospace Engineering, Technion–Israel Institute of Technology, Haifa, Israel

The paper develops the closed-form solution for the motion around an oblate planet in the situation when the orbit is unbounded. It is proven that when the effect of the J_2 zonal harmonic is taken into account, the orbit is different from its Keplerian counterpart, having a marked influence on the deflection angle, thereby changing the Keplerian flyby geometry. Numerical simulations quantify this difference, which is closely related to the minimum flyby altitude of the spacecraft. The analytic developments can be applied to the preliminary design of gravity-assisted maneuvers.
[View Full Paper]

AAS 12 – 164

Design of Optimal Transfers between North and South Pole-Sitter Orbits

Jeannette Heiligers, **Matteo Ceriotti**, **Colin R. McInnes** and **James D. Biggs**,
Advanced Space Concepts Laboratory, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, Scotland, United Kingdom

Recent studies have shown the feasibility of an Earth pole-sitter mission, where a spacecraft follows the Earth's polar axis to have a continuous, hemispherical view of one of the Earth's Poles. However, due to the tilt of the polar axis, the North and South Poles are alternately situated in darkness for long periods during the year. This significantly constrains observations and decreases mission scientific return. This paper therefore investigates transfers between north and south pole-sitter orbits before the start of the Arctic and Antarctic winters to maximize scientific return by observing the polar regions only when lit. Clearly, such a transfer can also be employed for the sole purpose of visiting both the North and South Poles with one single spacecraft during one single mission. To enable such a novel transfer, two types of propulsion are proposed, including solar electric propulsion (SEP) and a hybridization of SEP with solar sailing. A direct optimization method based on pseudospectral transcription is used to find both transfers that minimize the SEP propellant consumption and transfers that trade-off SEP propellant consumption and observation time of the Poles. Also, a feedback control is developed to account for non-ideal properties of the solar sail. It is shown that, for all cases considered, hybrid low-thrust propulsion out-performs the pure SEP case, while enabling a transfer that would not be feasible with current solar sail technology.
[View Full Paper]

AAS 12 – 165

Efficient Lunar Gravity Assists for Solar Electric Propulsion Missions

Damon Landau, **Tim P. McElrath**, **Dan Grebow** and **Nathan J. Strange**,
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The combination of lunar gravity assists for Earth escape and ~1.25 yr. of SEP V-infinity leveraging effectively boosts the performance of a given launch vehicle. Two methods are available to establish a launch period with lunar gravity assists, where the energy achievable with lunar escape has been characterized as a function of right ascension, declination, and launch energy. The increased launch efficiency makes a Falcon 9 perform like an Atlas V (401) at low C_3 or like an Atlas V (531) at high C_3. An Atlas V (551) outperforms a Delta IV Heavy for C_3 above 24 km^2/s^2. [View Full Paper]

AAS 12 – 166
(Paper Withdrawn)

AAS 12 – 167

Optimization of Debris Removal Path for TAMU Sweeper

Jonathan Missel and **Daniele Mortari**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

This paper provides a path optimization strategy for debris removal satellites, focusing on the proposed *TAMU Sweeper* mission. The optimized solution is a set of *n* satellite maneuvers, *n* debris captures, and *n* debris ejections. Ejected debris are sent to lower perigee orbits or to re-enter the atmosphere. Optimization is performed using an evolutionary algorithm that solves the combinatory problem of selecting the debris interaction order, transfer trajectories, and sequence timing, while optimizing fuel cost and effectiveness towards debris mitigation. For a fixed time interval and number of debris interactions, the most efficient and effective sequence is sought. The broader goal of this work is to evaluate feasibility of such missions. Our early findings show that the *TAMU Sweeper* technique directly removes 81% of the debris encountered through re-entry, and significantly lowers the perigees of the rest. It does so while using 40% less fuel than "traditional" successive rendezvous approaches. [View Full Paper]

SESSION 9: ATTITUDE DYNAMICS AND CONTROL I

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

AAS 12 – 168

Delayed Feedback Attitude Control Using Neural Networks and Lyapunov-Krasovskii Functionals

Ehsan Samiei, **Morad Nazari** and **Eric A. Butcher**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.; **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

This paper addresses the regulation control and stabilization problem of spacecraft attitude dynamics when there exists an unknown constant discrete delay in the measurements. Radial basis function neural networks are used to approximate the kinematics and inertial nonlinearities while a back propagation algorithm is employed to update neural network weights. By employing a Lyapunov-Krasovskii functional, a delay independent stability condition is obtained in terms of a linear matrix inequality, the solution of which gives the suitable controller gains. Finally, to show the effectiveness of the proposed controller, a set of simulations are performed and the results of the proposed control strategy are compared with results obtained using the method for delayed attitude control suggested by Ailon *et al.* [View Full Paper]

AAS 12 – 169

A New Method for Simulating the Attitude Dynamics of Passively Magnetically Stabilized Spacecraft

Roland Burton and **Joseph Starek**, Stanford University, Stanford, California, U.S.A. and NASA Ames Research Center, Moffett Field, California, U.S.A.;
Stephen Rock, Stanford University, Stanford, California, U.S.A.

A new method for simulating the behavior of magnetically permeable material is presented that offers an order of magnitude reduction in simulation run time compared to existing methods with no loss in accuracy. The new method was integrated into a full attitude dynamics simulation of the NASA O/OREOS spacecraft and preliminary comparisons between the simulation results and orbit data are made. [View Full Paper]

AAS 12 – 170

Design of Satellite Control Algoritm Using the State-Dependent Riccati Equation and Kalman Filter

Luiz C. G. de Souza, National Institute for Space Research, São Paulo, Brazil;
Victor M. R. Arena, Federal University of ABC, Santo André, São Paulo, Brazil

A properly attitude control algorithm design and test procedure can dramatically minimize space mission costs by reducing the number of errors that can be transmitted to the next phase of the project. Besides, when attitude control algorithm problems are discovered on-orbit the mission or at least part of it can be lost. One way to increase confidence in the control algorithm is its experimental validation through prototypes. The Space Mechanics and Control Division (DMC) of INPE is constructing a 3D simulator to supply the conditions for implementing and testing satellite hardware and software. The 3D simulator can accommodate various satellites components; like sensors, actuators, computers and its respective interface and electronic. Depending on the manoeuvre the 3D simulator plant can be highly non-linear and if its inertia parameters are not well determined the plant can also present some kind of uncertainty. As a result, controller designed by linear control technique can have its performance and robustness degraded. This paper presents the application of the State-Dependent Riccati Equation (SDRE) method in conjunction with Kalman filter to design and test a attitude control algorithm for a 3D satellite simulator. The control strategy is based on gas jets and reaction wheel torques to perform large angle manoeuvre in three axes. The simulator model allows investigating the dynamics and the control system taking into account effects of the plant non-linearities and system noise. Initially, a simple comparison between the LQR and SDRE controller is performed. Practical applications are presented to address problems like presence of noise in process and measurements and incomplete state information using Kalman filter technique. Simulation has shown the performance and robustness of the SDRE controller applied for angular velocity reduction associated with stringent pointing requirement. [View Full Paper]

AAS 12 – 171

Artificial Potential Steering for Angular Momentum Exchange Devices

Josue D. Muñoz and **Frederick A. Leve**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland, AFB, New Mexico, U.S.A.

Artificial potential function methodology is well-suited for steering of angular momentum exchange devices (AMED) since path constraints (i.e., saturation and singularities) can be imposed using artificial potentials. The angular momentum artificial potential steering (AMAPS) method is developed by first defining a reference trajectory for the angular momentum of the AMED. Next, angular momentum saturation for both reaction wheel assemblies (RWA) and control moment gyros (CMG) are handled by using a repulsive artificial potential function. Singularities of CMGs are handled by defining a repulsive potential to ensure that the Jacobian stays full rank. [View Full Paper]

AAS 12 – 172

Converting Repetitive Control Robustification Methods to Apply to Iterative Learning Control

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

Iterative learning control (ILC) can be used for high accuracy tracking with fine pointing equipment on board spacecraft that need to perform repeated scanning maneuvers. In previous research, frequency response based methods were developed for repetitive control (RC) design that average a cost function over a distribution of models. The result is that the designs produced are much more robust to model parameter error. ILC is a sister field to RC, but aims for zero tracking error in finite time trajectories. This paper makes use of the relationship between frequency response and the singular value decomposition of a Toeplitz matrix of Markov parameters, in order to extend frequency response concepts to finite time problems. Then three kinds of robustification of ILC design are accomplished that parallel the results in RC. These include: (1) Robustification produced by adjusting the phase compensation at each frequency based on the distribution of model phases. (2) Adjusting the gain of the RC compensator as a function of frequency for improved robustification in exchange for slower learning of error components at some frequencies. And, (3) adjusting the stability boundary as a function of frequency, which obtains robustness at the expense of not asking for zero error for certain frequency components. Numerical examples are given that illustrate that one can design ILC laws that take advantage of all of these methods of robustification.
[View Full Paper]

AAS 12 – 173

De-Orbit Attitude Dynamics and Control of Spacecraft with Residual Fuel Based on Fluidic Ring Actuator

Hong Guan and **Shijie Xu**, Department of Aerospace Engineering, School of Astronautics, Beihang University, Beijing, China

This work presents a novel approach for the attitude control of spacecraft during the de-orbit process. It implements the fluidic rings as the momentum exchange device to stabilize the orientation of spinning axis and damp the disturbance torque of liquid sloshing and environmental disturbances. Fluidic rings utilize the residual fuel in the tank and accelerate them in the rings by the pump to produce the required torque. The dynamics of a vehicle with three fluid rings is developed first. The influence of the liquid sloshing is incorporated by the computational fluid dynamics (CFD) method. Then, a control law is designed by Lyapunov method. Numerical simulations are given to demonstrate the effectiveness of the proposed control schemes. [View Full Paper]

AAS 12 – 174

A Computational Efficient Suboptimal Algorithm for Dynamic Thruster Management

Mengping Zhu, **Hong Guan** and **Shijie Xu**, Department of Aerospace Engineering, School of Astronautics, Beihang University, Beijing, China

This paper emphasizes on the design of a dynamic suboptimal thrust selection algorithm for reaction control system with redundant configured thrusters. Differing from using the thruster management function cone (TMF_cone) to construct special look-up tables that store the precomputed optimal bases of the auxiliary problem, this algorithm is based on the cascaded searching of the optimal or the suboptimal TMF_cone. During each iteration of the algorithm, an optimal or near optimal TMF_cone for the unconstrained thruster management problem is first found. Then, minimum and maximum open times are taken into account to manage commands exceeding the up or lower limit of the constraints. Control error is calculated for next iteration until it finally comes to zero and no more thrusters exceed the constraints. An Illustrative example based on the core module of the space station is provided to verify the effectiveness and correctness of the proposed method as well as to demonstrate its advantage in computational requirement and adaptiveness to thruster failure. [View Full Paper]

AAS 12 – 175

Analysis of Small-Time Local Controllability of Spacecraft Attitude Using Two Control Moment Gyros

Haichao Gui, **Hong Guan**, **Shijie Xu** and **Lei Jin**, Department of Aerospace Engineering, School of Astronautics, Beihang University, Beijing, China

Small-time local controllability (STLC) of the combined dynamics comprising the spacecraft and two non-coaxially or coaxially arranged single-gimbal control moment gyros (CMGs) is investigated in sequence. Nonlinear controllability theory is used to shown that for the case of two non-coaxial CMGs, the combined dynamics are STLC at the equilibrium if and only if the two angular momentum vectors of two CMGs do not both lie along the same direction or in the plane spanned by two gimbal axis vectors. For the case of two coaxial CMGs, the combined dynamics are STLC at the equilibrium if the angular momentum vectors of two CMGs do not become collinear.
[View Full Paper]

SESSION 10: FLIGHT DYNAMICS OPERATIONS
Chair: Laurie Mann, a.i. solutions Inc.

AAS 12 – 176

Effects of High Frequency Density Variations on Orbit Propagation

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

Accelerometer derived densities for CHAMP and GRACE have multiple high frequency variations that are not present in empirical density models or in density derived from precision orbit ephemeris (POE) data. These high frequency density variations appear in all data sets, but are especially prevalent during geomagnetic storms, near the polar cusps, and when the orbit plane is near the terminator. This paper examines the effects of these high frequency density variations on orbit propagation by comparing orbits propagated using accelerometer derived density to those propagated using POE derived density, High Accuracy Satellite Drag Model density, and Jacchia 71 density.
[View Full Paper]

AAS 12 – 177

End of Life Procedures for Air Force Missions: CloudSat and TacSat-3

Michael V. Nayak, Research, Development, Test and Evaluation (RDT&E) Support Center (RSC), Space Development and Test Directorate, Kirtland Air Force Base, New Mexico, U.S.A.

At altitudes of less than 2,000 km., fragmentation wreckage caused by accidental explosions aboard spacecraft accounts for 42% of catalogued space debris, spanning all sizes and widely distributed through the orbits of their host satellites. Using currently operational satellites CloudSat and TacSat-3 as examples, this paper discusses Air Force Space Command, NASA and Department of Defense requirements for mitigation of orbital debris during creation of an End of Life (EOL) plan, and lays out an outline for writing such plans with special applicability to military missions. EOL spacecraft passivation, re-entry survivability analysis, casualty expectation analysis, methods to assess debris generation at EOL due to intentional breakup activities, passivation, accidental explosions, and on-orbit collisions; as well as operational execution of EOL for both maneuverable and non-maneuverable space vehicles, with a specific focus on Low Earth Orbit satellites that are unable to relocate to a graveyard orbit, are covered.
[View Full Paper]

AAS 12 – 178

Extended Mission Maneuver Operations for the Interstellar Boundary Explorer (IBEX)

Ryan Lebois, **Lisa Policastri**, **John Carrico Jr.** and **Marissa Intelisano**, Applied Defense Solutions Inc., Columbia, Maryland, U.S.A.

This paper describes the operational strategies designed and executed by the IBEX Flight Dynamics Group to transfer IBEX from its nominal science orbit onto a Lunar-Resonant trajectory that is predictable beyond the expected lifetime of the spacecraft. This paper will highlight operational constraints involved in planning the Orbit Maintenance Maneuvers (OMMs) as well as the steps involved in calibrating the maneuvers, replanning the maneuvers during operations, and analyzing the success of the OMM execution based on operational results. A comparison of current orbit predictions with the final pre-maneuver plan will also be discussed. [View Full Paper]

AAS 12 – 179

Flight Results of the Precise Autonomous Orbit Keeping Experiment on the PRISMA Mission

Sergio De Florio and **Gianmarco Radice**, Advanced Research Team, School of Engineering, University of Glasgow, Glasgow, Scotland, United Kingdom;
Simone D'Amico, GSOC/Space Flight Technology, Wessling, Germany

The Autonomous Orbit Keeping (AOK) experiment on the PRISMA mission was executed successfully from the 18th of July to the 16th of August 2011 and has demonstrated the capability of autonomous precise absolute orbit control. Using GPS-based absolute navigation data, AOK commanded thruster activations in the orbital frame to autonomously control the satellite's longitude of ascending node (LAN) within a predefined window. The main performance requirement of the experiment was a control accuracy of the LAN of 10 m (1σ) with a maneuver velocity increment-decrement available budget of 0.5 m/s. After a 4-days commissioning phase, the reference orbit was acquired. A 3.5-days controller tuning was then followed by the fine orbit control phase started on the 30th of July until the end of the experiment. The control accuracy requirement was fulfilled. The mean value of the LAN deviation controlled by AOK was -3.6 m with a standard deviation of 9.5 m during the fine control phase. The total delta-v spent during the entire experiment was 0.1347 m/s corresponding to 27% of the maneuvers budget allocated. Digital Video System (DVS) data-takes on Earth have played an important role in the planning and execution of the AOK experiment as they mimic a remote sensing payload. [View Full Paper]

AAS 12 – 180

Numerical Prediction of Satellite Surface Forces with Application to Rosetta

Benny Rievers, **Takahiro Kato** and **Claus Laemmerzahl**; Center for Applied Space Technology and Microgravity, ZARM, University of Bremen, Bremen, Germany;
Jozef C. van der Ha, Consultant, Spacecraft Design/Operations, Bensheim, Germany

Precise orbit determination and propagation depends on the accurate modeling of all perturbations acting on a spacecraft orbit. While the gravitational influences (including relativistic effects) can be described accurately by the motion of point masses, most non-gravitational effects interact with the spacecraft surfaces and thus depend on the actual sizes, shapes and thermo-optical properties of these surfaces. A proper analysis of these surface forces demands the implementation of a detailed geometrical model as well as a detailed model of the physical interactions between the space environment and the spacecraft. We present a numerical approach based on finite elements and ray-tracing which is worked out for the analysis of Solar radiation pressure (SRP) and thermal recoil pressure (TRP). The models are used for the evaluation of the influence of SRP and TRP on the Rosetta trajectory during its heliocentric cruise phases as well as for the first Rosetta Earth fly-by. The results show that TRP has the magnitude of about 10% of the SRP. Neither of these effects can explain the anomalous delta v gain observed for the first Earth fly-by which is in agreement with results obtained by corresponding analytical methods. [View Full Paper]

AAS 12 – 181

Mass Ejection Anomaly in Lissajous Orbit: Response and Implications for the ARTEMIS Mission

Brandon D. Owens, **Daniel P. Cosgrove**, **Jeffrey E. Marchese**, **John W. Bonnell**, **David H. Pankow**, **Sabine Frey** and **Manfred G. Bester**, Space Sciences Laboratory, University of California, Berkeley, California, U.S.A.

On October 14, 2010, a 0.092 kg instrument sphere unexpectedly detached from the first spacecraft to ever orbit an Earth-Moon libration point. At the time of the anomaly, the spacecraft—which was one of two spacecraft dedicated to the ARTEMIS mission—had been in orbit about the L2 Earth-Moon libration point for less than two months and its operations team was still adjusting to the intricacies of Lissajous orbit operations. Nevertheless, a quick response was required to prevent the spacecraft from falling out of Lissajous orbit and set it up for several months of continued Lissajous orbit operations followed by an insertion into a retrograde lunar orbit. In this paper, the actions of this team and the changes to the spacecraft's flight characteristics are described for the benefit of future Earth-Moon libration point orbiting missions. Specifically, the authors detail how the response affected the prospects of preventing the spacecraft's fall out of Lissajous orbit. These details are then used to form recommendations on spacecraft design, attitude control, and tracking schemes that can mitigate the impact of mass ejection or errant thrust events in Lissajous orbit. Additionally, the authors present several of the dynamics phenomena observed during the event in the form of "homework" or "exam" problems that could be used for teaching, interviewing, or testing science and engineering students and professionals. [View Full Paper]

AAS 12 – 182

Optimizing ARTEMIS Libration Point Orbit Stationkeeping Costs through Manuever Performance Calibration

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

The first two spacecraft to orbit Earth-Moon libration points—ARTEMIS P1 and P2—performed a combined total of 67 stationkeeping maneuvers over a period of 10 months. The degree of precision required for these small-scale orbit corrections exceeded the degree that had been obtained on these spacecraft in the years leading up to their Lissajous orbit insertions. Therefore, an effort was undertaken to improve maneuver performance in the initial and preceding months of this stationkeeping experience. This paper includes details of the inflight calibration techniques used to obtain the improved level of performance for these maneuvers. It expands on previously reported THEMIS/ARTEMIS maneuver calibration techniques and results through discussion of newly uncovered issues with maneuver performance modeling, the introduction of new calibration approaches, and the presentation of stationkeeping data. With these procedures and issue resolutions in place, the operations team routinely reduced maneuver magnitude and phase errors to less than 2 mm/s and one degree, respectively (the minimum maneuver magnitude error was 46.3 μm/s). These error reductions ultimately reduced the total ΔV expenditure during Lissajous orbit operations and gave the maneuver designers the flexibility to vary the amount of time between stationkeeping events from 4.6 days to 14.2 days. [View Full Paper]

AAS 12 – 183

Optimizing Solar Radiation Coefficient as a Solve-for Parameter for the Orbit Determination Process during the Libration-Point Orbit Phase of the ARTEMIS Mission

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

The first two spacecraft to orbit Earth-Moon libration points—ARTEMIS P1 and P2—performed a total of 67 station-keeping maneuvers over a period of 10 months. With short durations between maneuvers and software restrictions that required data arcs be reset subsequent to each maneuver, it was critical to ensure that successive orbit determinations converged to an accurate solution in a timely manner. This paper details the in-flight techniques used to optimize solve-for parameters—such as the solar radiation coefficient, along with a constraint on its standard deviation—in the orbit solutions to ensure accuracy while still providing short convergence intervals. We present the collected data and we describe the application of our method for predicting orbit solution uncertainty in planning for the ARTEMIS Lunar orbit insertion operations.
[View Full Paper]

SESSION 11: DYNAMICAL SYSTEMS THEORY II
Chair: Dr. David Spencer, Pennsylvania State University

AAS 12 – 184
Optimized Three-Body Gravity Assists and Manifold Transfers in End-to-End Lunar Mission Design

Piyush Grover, Mitsubishi Electric Research Labs, Cambridge, Massachusetts, U.S.A.; **Christian Andersson**, Centre for Mathematical Sciences, Lund University / Modelon AB, Sweden

We describe a modular optimization framework for GTO-to-moon mission design using the planar circular restricted three-body problem (PCR3BP) model. The three-body resonant gravity assists and invariant manifolds in the planar restricted three-body problem are used as basic building blocks of this mission design. The mission is optimized by appropriately timed delta-Vs, which are obtained by a shooting method and a Gauss-Pseudospectral collocation method for different phases of the mission. Depending upon the initial and final orbits, the optimized missions consume between 10-15 % less fuel compared to a Hohmann transfer, while taking around 4 to 5 months of travel time. [View Full Paper]

AAS 12 – 185
Tisserand-Leveraging Transfers

Stefano Campagnola, **Daniel J. Grebow** and **Anastassios E. Petropoulos**, Outer Planet Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **Arnaud Boutonnet** and **Johannes Schoenmaekers**, Mission Analysis Section, European Space Operation Center, ESA, Darmstadt, Germany; **Ryan P. Russell**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas, U.S.A.

Tisserand-leveraging transfers (TILTs) are introduced as a new method for computing low Δv orbit transfers with the help of third-body perturbations. The TILTs can mitigate the costs and risk of planetary missions by reducing the orbit insertion maneuver requirements while maintaining short flight times. TILTs connect two flybys at the minor body with an impulsive maneuver at an apse. Using the circular, restricted, three-body problem, TILTs extend the concept of v-infinity leveraging beyond the patched-conics domain. In this paper a new method is presented to compute TILTs and to patch them together to design low-energy transfers. The presented solutions have transfer times similar to the high-energy solutions, yet the Δv cost is significantly reduced (up to 60%), thus enabling new orbiter missions to planetary satellites. For this reason, TILTs are used in the reference endgame of ESA's new mission option to Ganymede, JUICE, which is also presented here. The "lunar resonances" of SMART1 are also explained in terms of low-thrust TILTs, suggesting future application of TILTs and low-thrust TILTs to design mission to the Moon and to other small body destinations. Finally, a new model called "conic-patched, multi-body model" is introduced to allow a fast and accurate integration of the multi-body dynamics, and has applications beyond TILTs. [View Full Paper]

AAS 12 – 186

Improving Vehicle Reusability for Human Exploration of Near-Earth Asteroids Using Sun-Earth Libration Point Orbits

Aline K. Zimmer and **Ernst Messerschmid**, Institute of Space Systems, University of Stuttgart, Germany

Current plans for human exploration of the solar system envision several missions to Near-Earth Asteroids (NEAs) as stepping stones towards missions to Mars. This research investigates the feasibility of stationing reusable cargo spacecraft, such as habitats, in halo orbits at Sun-Earth Libration points 1 and 2 (L_1 and L_2) between NEA missions in an effort to reduce mission cost and thus overall campaign cost by lowering the mass required to be launched and the amount of new hardware to be built for each mission. Four example missions to the two currently most promising targets of the known NEA population in the 2025-2030 time frame are chosen. In the mission architecture proposed in this study, the crew vehicle directly commutes between Earth and the asteroid in order to keep mission durations for the crew short. The cargo vehicle depart from a halo orbit, rendezvous with the crew vehicle on the outbound trajectory, and returns to a halo orbit after the mission. Manifold trajectories of halo orbits in the northern and southern halo orbit family at L_1 and L_2 are considered for the transfer of the cargo vehicle to and from the interplanetary trajectory and the total Δv required for this transfer is minimized. This Δv is found to range from a few meters per second to hundreds of meters per second, depending on the specific energy and inclination of the interplanetary trajectory. These results show the great potential of the utilization of Sun-Earth libration point orbits for enabling vehicle reusability, thus lowering the cost of human exploration missions. [View Full Paper]

AAS 12 – 187

Preliminary Study of the Transfer Trajectory from the Moon to the Halo Orbit for the Small Scientific Spacecraft, DESTINY

Masaki Nakamiya and **Yasuhiro Kawakatsu**, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

This study investigates the trajectory design of the small scientific spacecraft, DESTINY (Demonstration and Space Technology for INterplanetary voYage), which aims to be launched by the third Japanese next-generation solid propellant rocket (Epsilon rocket) around 2017. In the DESTINY mission, the spacecraft will go to the moon by the ion engine from the large ellipse orbit. Afterward, by using the lunar swing-by, the spacecraft will put into the periodic orbit in the vicinity of the libration point (Halo orbit) of the Sun-Earth L2. This study focuses on the transfer trajectories from the moon to the Halo orbit. [View Full Paper]

AAS 12 – 188

Circular Restricted Three-Body Problem with Photonic Laser Propulsion

F. Y. Hsiao, **P. S. Wu**, **Z. W. Cheng**, **Z. Y. Yang**, **J. W. Sun**, **H. K. Chen**, **H. Y. Chen**, **Y. T. Jan** and **D. H. Lien**, Department of Aerospace Engineering, Tamkang University, Tamsui, Taiwan, R.O.C.

This paper studies the trajectory of spacecraft propelled by the photonic laser propulsion (PLP) system under the environment of circular restricted three-body problem (CRTBP). The PLP system is an innovative technology proposed by Dr. Bae. With repeated reflections of laser beam, it can generate continuous and tremendous power by consuming very small energy. In 2011, the application of PLP propelled spacecraft in the Martian mission is investigated under the two-body-problem assumption. In practical problems, however, the gravity of the Earth is not negligible. As a result, in this paper we study the trajectory under the CRTBP. At the beginning, the PLP system is briefly introduced. Then we prove that the PLP system can be modeled as a force potential, so that the conventional procedure of analysis to the CRTBP can be applied. Numerical simulations are also provided to demonstrate the effects of the PLP system.
[View Full Paper]

AAS 12 – 189

Canonical Perturbation Theory for the Elliptic Restricted-Three-Body Problem

Brenton Duffy and **David F. Chichka**, Department of Mechanical and Aerospace Engineering, George Washington University, Washington, D.C., U.S.A.

The distinguishing characteristic of the elliptic restricted three-body problem is a time-varying potential field resulting in non-autonomous and non-integrable dynamics. The purpose of this study is to normalize the system dynamics about the circular case and about one of the triangular Lagrange points by applying a method of canonical perturbation theory introduced by Hori and Deprit in the 1960s. The classic method derives a near-identity transformation for a Hamiltonian function expanded about a single parameter such that the transformed form possesses ideal properties of integrability. In this study, the method is extended to two-parameter expansions and applied to motion about the triangular elliptic Lagrange points. The transformed system is expressed in Birkhoff normal form for which the stability properties may be analyzed using KAM theory and the motion by local integrals and level sets. [View Full Paper]

AAS 12 – 190

A Visual Analytics Approach to Preliminary Trajectory Design

Wayne R. Schlei and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

Recent developments in astrodynamics suggest a wealth of design potential within the context of the circular restricted three-body problem. Exploitation of the expanding dynamical and mathematical insights, though, has been difficult to capture within a real-time design setting. Emerging from the ability to represent large amounts of information through visual environments, visual analytics is a new science that focuses on the application of graphical depictions to facilitate discovery. Moreover, visual analytics blends the science of analytical reasoning with the implementation of interactive visual interfaces. In considering the most effective approach to incorporate visual elements in a largely automated process, this investigation blends the fundamentals of trajectory design in multi-body regimes with the implementation of visual analytics, thereby merging visualization tools, differential corrections algorithms, and the intuition of a knowledgeable designer into one expansive design approach. Visual analytics offers a basis for rapid investigation and design with access to a wider range of options for the construction of trajectories that meet mission requirements. [View Full Paper]

SESSION 12:
SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL I
Chair: Dr. Shyam Bhaskaran, Jet Propulsion Laboratory

AAS 12 – 191
Adaptive Pinpoint and Fuel Efficient Mars Landing Using Reinforcement Learning

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

Future unconstrained and science-driven missions to Mars will require advanced guidance algorithms that are able to adapt to more demanding mission requirements, e.g. landing on selected locales with pinpoint accuracy while autonomously flying fuel-efficient trajectories. In this paper, we will present a novel guidance algorithm designed by applying the principles of Reinforcement Learning (RL) theory. The goal is to devise an adaptive guidance algorithm that enables robust, fuel efficient, and accurate landing without the need for off-line trajectory generation. Results from a Monte Carlo simulation campaign show that the algorithm is capable of autonomously flying trajectories that are close to the optimal minimum-fuel solutions with an accuracy that surpasses conventional Apollo-like guidance algorithms. The proposed RL-based guidance algorithm exhibits a high degree of flexibility and can easily accommodate autonomous retargeting while maintaining accuracy and fuel efficiency. Although reinforcement learning and other similar machine learning techniques have been previously applied to aerospace guidance and control problems (e.g., autonomous helicopter control), this appears, to the best of our knowledge, to be the first application of reinforcement learning to the problem of autonomous planetary landing. [View Full Paper]

AAS 12 – 192
Design and Assessment of Open-Loop Variable Ignition Time Guidance for the Mars Ascent Vehicle

Kevin E. Witzberger, Mission Design and Analysis Branch, NASA Glenn Research Center, Cleveland, Ohio, U.S.A.; **David A. Smith**, Wyle LLC, supporting the Mission Design and Analysis Branch, NASA Glenn Research Center, Cleveland, Ohio, U.S.A.

This paper describes a variable upper stage ignition time open-loop guidance scheme for NASA's Mars ascent vehicle (MAV). An optimal two-stage trajectory is found using OTIS. The scheme utilizes a table lookup of optimal OTIS Euler angles for the powered portion of flight. A Newton-Raphson root-finding technique determines the upper stage ignition time that ensures the final altitude constraints are satisfied. Allowing the ignition time to be a free variable is a simple and straightforward way to accommodate environmental and hardware performance variations. The guidance scheme is implemented in a three degree-of-freedom (3-DOF)/6-DOF vehicle simulation program named MASTIF. We test the robustness of the guidance scheme with Monte Carlo dispersion simulations. [View Full Paper]

AAS 12 – 193
(Paper Withdrawn)

AAS 12 – 194
Flight Path Control for Solar Sail Spacecraft

Geoffrey G. Wawrzyniak and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

Recent investigations of trajectory options that incorporate solar sails have been motivated by missions to observe planetary poles or to communicate with an outpost at the lunar south pole. Designing reference trajectories and understanding their fundamental dynamics are necessary first steps toward flying spacecraft in dynamically complicated regimes. However, the existence of a reference orbit alone is insufficient for flight operations. Two variations of a turn-and-hold strategy are examined for flight-path control: an approach that implements multiple turns to achieve a target in an error-free scenario and an approach that incorporates a look-ahead strategy to accommodate representative errors. [View Full Paper]

AAS 12 – 195
Integrated Guidance and Attitude Control for Pinpoint Lunar Guidance Using Higher Order Sliding Modes

Daniel R. Wibben and **Roberto Furfaro**, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.

A novel non-linear guidance and attitude control scheme for pinpoint lunar landing is presented. The development of this algorithm is motivated by the desire to increase landing accuracy due to more stringent landing requirements in future lunar mission architectures and by the interest to integrate the attitude control and landing guidance into the same algorithm. Based on Higher Order Sliding Mode control theory, the proposed Multiple Sliding Surface Guidance and Control (MSSGC) algorithm has been designed to take advantage of the ability of the system to converge to the sliding surface in a finite time. The proposed MSSGC does not require the generation of a trajectory off-line and therefore it is very flexible without the need of off-line trajectory generation. The proposed guidance law is proven globally stable using a Lyapunov-based approach. Results from a set of parametric studies demonstrate that the MSSGC law not only drives the spacecraft to the desired position with zero velocity, but also with the desired attitude and angular rates. [View Full Paper]

AAS 12 – 196

Waypoint-Optimized Zero-Effort-Miss / Zero-Effort-Velocity Feedback Guidance for Mars Landing

Yanning Guo, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, Heilongjiang, China; **Matt Hawkins** and **Bong Wie**, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

This paper investigates the optimization approach to generate waypoints for the Mars landing problem in the context of employing the Zero-Effort-Miss/Zero-Effort-Velocity (ZEM/ZEV) feedback guidance algorithm. For a power-limited engine, the waypoint optimization problem in the presence of state constraints is converted to an equivalent standard quadratic programming problem, which can be solved efficiently. In the case with a thrust-limited engine, by introducing a continuously differentiable function to approximate the standard saturation function, the optimal waypoint can be determined using open-source optimization software. This novel idea exploits parameter optimization techniques for feedback control implementation, thus it can combine the advantages of open-loop and closed-loop methods to achieve near-optimal performance with acceptable robustness, while meeting various practical constraints and requirements. [View Full Paper]

AAS 12 – 197

Applications of Generalized Zero-Effort-Miss / Zero-Effort-Velocity Feedback Guidance Algorithm

Yanning Guo, Department of Control Science and Engineering, Harbin Institute of Technology, Harbin, Heilongjiang, China; **Matt Hawkins** and **Bong Wie**, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

The performance of the zero-effort-miss/zero-effort-velocity (ZEM/ZEV) feedback guidance algorithm is evaluated through practical space application examples. The ZEM/ZEV feedback guidance algorithm is in general not an optimal solution; however, it is an optimal solution in a uniform gravitational environment. It is also conceptually simple and easy to implement, and thus has great potential for autonomous on-board implementation. It is shown that, for some classic ballistic missile intercept and asteroid intercept scenarios, the ZEM/ZEV algorithm can even compete with corresponding open-loop optimal solutions, while its feedback characteristics make it more suitable to deal with uncertainties and perturbations. By employing the ZEM/ZEV algorithm in the highly nonlinear orbital transfer and raising problems and comparing with corresponding open-loop optimal solutions, its simplicity and near-optimality are further verified. [View Full Paper]

SESSION 13: ORBIT DETERMINATION I
Chair: Dr. W. Todd Cerven, The Aerospace Corp.

AAS 12 – 198
Dual Accelerometer Usage Strategy for Onboard Space Navigation

Renato Zanetti, Vehicle Dynamics and Controls, The Charles Stark Draper Laboratory, Houston, Texas, U.S.A.; **Chris D'Souza**, Aeroscience and Flight Mechanics Division, NASA Johnson Space Center, Houston, Texas, U.S.A.

This work introduces a dual accelerometer usage strategy for onboard space navigation. In the proposed algorithm the accelerometer is used to propagate the state when its value exceeds a threshold and it is used to estimate its errors otherwise. Numerical examples and comparison to other accelerometer usage schemes are presented to validate the proposed approach. [View Full Paper]

AAS 12 – 199
Expected Navigation Flight Performance for the Magnetospheric Multiscale (MMS) Mission

Corwin Olson, **Cinnamon Wright** and **Anne Long**, a.i. solutions, Inc., Lanham, Maryland, U.S.A.

The Magnetospheric Multiscale (MMS) mission consists of four formation-flying spacecraft placed in highly eccentric elliptical orbits about the Earth. The primary scientific mission objective is to study magnetic reconnection within the Earth's magnetosphere. The baseline navigation concept is the independent estimation of each spacecraft state using GPS pseudorange measurements (referenced to an onboard Ultra Stable Oscillator) and accelerometer measurements during maneuvers. State estimation for the MMS spacecraft is performed onboard each vehicle using the Goddard Enhanced Onboard Navigation System, which is embedded in the Navigator GPS receiver. This paper describes the latest efforts to characterize expected navigation flight performance using upgraded simulation models derived from recent analyses. [View Full Paper]

AAS 12 – 200

Minimum L1 Norm Orbit Determination Using a Sequential Processing Algorithm

Steven Gehly, **Brandon Jones**, **Penina Axelrad** and **George Born**, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Colorado, U.S.A.

Most least squares orbit estimation methods assume that observation errors are well described by a Gaussian distribution. In reality, the tracking of space objects via ground-based systems yields observations that are sparse and highly irregular, invalidating the Gaussian assumption and potentially reducing orbit estimation accuracy. Instead of the assumption of a strictly Gaussian observation error distribution, this paper considers a mixture model method based on the Huber cost function. The estimation technique weighs observations consistent with the innovation variance using the l_2-norm and inconsistent observations using the more robust l_1-norm. This paper presents a numerically stable formulation of the Huber estimator for sequential orbit determination, and tests this method in a Sun-synchronous scenario with ground-based range and range-rate observations. The tests include a sensitivity Monte-Carlo study given a fixed number of random observation outliers for orbit estimation. For the case considered, a comparison between the Huber estimator, an extended Kalman filter (EKF), and an EKF with data editing capabilities demonstrates improved robustness for orbit estimation when using the mixture model. Results for filter performance in regard to accuracy and outlier mitigation are presented. [View Full Paper]

AAS 12 – 201

Orbit Determination Based on Variation of Orbital Error

Reza Raymond Karimi and **Daniele Mortari**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

A novel technique of angles-only initial initial orbit determination based on variations of orbital error is presented for the case of Keplerian orbit. The fact that the estimated orbit, both shape and orientation, should remain constant at every instant of time is the foundation of the new technique. The orbital elements are estimated for every measurement and the residuals of the orbit shape and orientation errors are minimized with respect to the unknown ranges. In this formulation, the spacecraft ranges (leading to position and velocity vectors) along with the orbital elements are estimated all together. This method is capable of using multiple observations which makes it suitable for coplanar orbit determination cases. [View Full Paper]

AAS 12 – 202

Relative Navigation for Satellites in Close Proximity Using Angles-Only Observations

Hemanshu Patel, Emergent Space Technologies, Greenbelt, Maryland, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.; **Shawn Allgeier**, Schafer Corporation, Albuquerque, New Mexico, U.S.A.; **Ryan Russell**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.; **Andrew Sinclair**, Department of Aerospace Engineering, Auburn University, Auburn, Alabama, U.S.A.

Relative navigation using angles-only observations is explored in this research. Previous work has shown that the unique relative orbit of a deputy satellite cannot be found using angles-only camera measurements from the chief satellite when a linear model of relative motion is used, due to a lack of observability. This work examines the possibility of partial observability, which in this case consists of a basis vector that corresponds to a family of relative orbits. An initial orbit determination (IOD) method is introduced that uses 3 Line-Of-Sight (LOS) measurements and provides an initial guess for the basis vector. This guess is differentially corrected with a batch estimator that takes in a full set of LOS measurements to hone in on a converged solution for the basis vector. [View Full Paper]

AAS 12 – 203

Preliminary Assessment of the Orbit Restitution Capability of a Multiple-Antenna GNSS Receiver on a Highly Elliptic Orbit Reaching above GNSS Altitude

Stefano Casotto and **Massimo Bardella**, Department of Physics & Astronomy, University of Padua, Padova, Italy; **Alberto Zin**, Thales Alenia Space-Italia, Vimodrone (MI), Italy

Astronomical missions are often characterized by high altitude, highly elliptic orbits. We report on the results of a study on the orbit determination capability of a receiver equipped with several GNSS antennas on a 1,000 km by 25,000 km altitude orbit. Detailed visibility analysis shows how this antenna array can help extend the tracking periods to GNSS constellations. Account is taken of the side lobe radio link allowed by the real GPS antennas radiation pattern. High accuracy orbit determination in the few centimeters range is shown to be possible due to the smooth character of the force field, even in the presence of unmodeled attitude variations. [View Full Paper]

AAS 12 – 204

Second-Order Kalman Filters Using Multi-Complex Step Derivatives

Vivek Vittaldev, **Ryan P. Russell** and **Nitin Arora**, University of Texas at Austin, Texas, U.S.A.; David Gaylor, Emergent Space Technologies, Inc., Greenbelt, Maryland, U.S.A.

The Second Order Kalman Filter (SOKF) uses a second order Taylor series expansion (TSE) to account for nonlinearities in an estimation problem. In this work, the derivatives required for the SOKF are computed using multicomplex (MCX) derivatives, coded in the Matlab programming language. This method uses function overloading in order to derive or compute the derivatives to machine precision without having to compute the derivatives analytically. Thus, the SOKF can be easily implemented, while at the same time having fewer tuning parameters than other high order filters. The standard SOKF is also extended by combining it with Gaussian Mixture models (GMM), which gives promising results. The filters have been used to estimate the state of a 1 DOF falling body. The results show that the MCX computes the required derivatives just as accurately as an analytical method and the SOKF and GMM modification perform well in terms of accuracy compared to other filters. Despite the ease of use and high accuracy benefits, a current drawback of the MCX method is compute speed. Methods for improving the speed are beyond the current scope and will be addressed in future works. [View Full Paper]

SESSION 14: LUNAR AND PLANETARY MISSIONS
Chair: Lauri Newman, NASA Goddard Space Flight Center

AAS 12 – 205

An Orbit Plan Toward Akatsuki Venus Reencounter and Orbit Injection

Yasuhiro Kawakatsu, **Stefano Campagnola**, **Chikako Hirose** and **Nobuaki Ishii**, ISAS/JAXA, Samihara, Kanagawa, Japan

On December 7, 2010, AKATSUKI, the Japanese Venus explorer reached its destination and tried to inject into a closed orbit around Venus. However, due to a malfunction of the propulsion system, the maneuver was interrupted and AKATSUKI escaped the Venus into an interplanetary orbit. Telemetry data from AKATSUKI suggests the possibility to perform orbit maneuvers to reencounter Venus and retry Venus orbit insertion. Reported in this paper is an orbit plan investigated under this situation. The latest results reflecting the maneuvers conducted in the autumn 2011 is introduced as well. [View Full Paper]

AAS 12 – 206

Practical Design of 3D Phasing Orbit in Lunar Transfer Trajectory

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

The moon is attracting attention again as a target of space exploration. To focus on the lunar transfer, there is a sequence named "phasing orbit" which is different from the widely used direct transfer sequence. In this method, the spacecraft is not directly injected into the translunar orbit, but stays on a long elliptical phasing orbit for revolutions. A major merit of this method is that, by using the phasing orbit as a buffer, the translunar orbit can be fixed for acceptable width of launch window. Discussed in the paper is the design method of the phasing orbit using a chart developed by the author named "TM diagram." [View Full Paper]

AAS 12 – 207

Mission Analysis for the JUICE Mission

A. Boutonnet and **J. Schoenmaekers**, Flight Dynamics Division, ESA-ESOC, Darmstadt, Germany

This paper presents the mission analysis of JUICE, a mission to study Jupiter, its environment and its Galilean moons. This mission, inherited from EJSM Laplace, features new phases, like the Europa fly-bys or the Jupiter high inclined orbits. The Europa phase required a very specific strategy that minimizes the radiation integrated dose. Jupiter high inclined orbits are obtained via resonant swing-bys with Callisto. There are also updates of Laplace like the low energy transfer to Ganymede, but also the Ganymede in-orbit science phase that uses frozen orbits based on the effect of Ganymede's gravity potential and Jupiter's attraction. [View Full Paper]

AAS 12 – 208

Sensitivity Analysis of the Non-Gravitational Perturbations on a Mercury Orbiter

Takahiro Kato, **Benny Rievers** and **Claus Laemmerzahl**, Center for Applied Space Technology and Microgravity, ZARM, University of Bremen, Bremen, Germany;
Jozef C. van der Ha, Consultant, Spacecraft Design and Operations, Deming, Washington, U.S.A.

This paper presents the effects of the non-gravitational forces acting on a Mercury orbiter. The Albedo and InfraRed radiations originating from Mercury's surface are expected to significantly influence the orbital motion of the orbiter. Therefore, we study the accelerations induced by the Albedo and InfraRed radiations from Mercury in addition to the Solar Radiation Pressure and the Thermal Recoil Pressure. In order to illustrate the practical relevance of the results, we employ the parameters and orbital elements of NASA's MESSENGER mission. The contributions of the Albedo reflection and the planetary InfraRed radiation have been formulated in terms of a straightforward practical model. The Thermal Recoil Pressure effects are within the range from 19 to 24 % relative to the SRP effects in the cases considered. They dominate the Albedo and InfraRed effects, at least in the direction along the Sun vector. [View Full Paper]

AAS 12 – 209
(Paper Withdrawn)

AAS 12 – 210
Preliminary Mission Design for a Far-Side Solar Observatory Using Low-Thrust Propulsion

Jonathan F. C. Herman and **Ron Noomen**, Delft University of Technology, Delft, The Netherlands

This paper discusses the preliminary mission design for a solar observatory placed on the far side of the Sun by means of solar electric propulsion to allow for prolonged far-side solar observation. The research also investigates the heliocentric inclination that can be achieved with current or near-term propulsion technology to evaluate the feasibility of high-latitude observations. The optimization of the low-thrust trajectories is achieved through a direct method in a two-body model, using a nonlinear programming method for optimization. [View Full Paper]

AAS 12 – 211
On-Orbit Sail Quality Evaluation Utilizing Attitude Dynamics of Spinner Solar Sailer IKAROS

Yuichi Tsuda, **Yuya Mimasu** and **Ryu Funase**, ISAS/JAXA, Samihara, Kanagawa, Japan; **Yoshinobu Okano**, Department of Aerospace System Engineering, Tokyo Metropolitan University, Hino, Tokyo, Japan

This paper describes a method of evaluating sail quality utilizing in-flight attitude behavior of spinning solar sailer IKAROS. Since the successful deployment of the sail, IKAROS has received SRP which strongly affects both translational and rotational motion of the spacecraft. The authors have derived the "Generalized Spinning Sail Model (GSSM)" to reproduce observed unique attitude behavior of IKAROS. Following the previous work, this paper attempts to relate the GSSM with sail quality such as sail shape and flatness. An optical FEM model is constructed to evaluate the precise SRP effect on the spacecraft, and some candidates of deformed sail shape is reproduced which is consistent with the observed attitude motion. We also conclude by the in-flight attitude behavior that the surface roughness of the IKAROS sail is 0.33% at minimum. [View Full Paper]

AAS 12 – 212

Transfer of Impact Ejecta Material from the Surface of Mars to Phobos and Deimos

Loïc Chappaz, **Henry J. Melosh**, **Mar Vaquero** and **Kathleen C. Howell**,
Purdue University, West Lafayette, Indiana, U.S.A.

The Russian Phobos-Grunt spacecraft originally planned to return a 200-gram sample of surface material from Phobos to Earth. Although it was anticipated that this material would mainly be from the body of Phobos, there is a possibility that the sample may also contain material ejected from the surface of Mars by large impacts. An analysis of this possibility is performed using the best current knowledge of the different aspects of impact cratering on the surface of Mars and of the production of high-speed ejecta that might reach Phobos or Deimos. [View Full Paper]

SESSION 15: NUMERICAL AND ANALYTICAL TRAJECTORY TECHNIQUES

Chair: Angela Bowes, NASA Langley Research Center

AAS 12 – 213

A Closed Form Solution of the Two Body Problem in Non-Inertial Reference Frames

Daniel Condurache, Department of Theoretical Mechanics, Technical University ”Gheorghe Asachi,” Iasi, Romania; **Vladimir Martinusi**, Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, Haifa, Israel

A comprehensive analysis, together with the derivation of a closed form solution to the two-body problem in arbitrary non-inertial reference frames are made within the present work. By using an efficient mathematical instrument, which is closely related to the attitude kinematics methods, the motion in the non-inertial reference frame is completely solved. The closed form solutions for the motion in the non-inertial frame, the motion of the mass center, and the relative motion are presented in the paper. Dynamical characteristics analogue to the linear momentum, angular momentum and total energy are introduced. In the general situation, these quantities may be determined as functions of time, and their derivation is presented within the paper. In the situation where the non-inertial frame has only a rotation motion, these quantities become first integrals in a larger sense, with respect to an adequately defined differentiation rule.
[View Full Paper]

AAS 12 – 214

A Survey of Symplectic and Collocation Integration Methods for Orbit Propagation

Brandon A. Jones, Colorado Center for Astrodynamics Research, University of Colorado at Boulder, Colorado, U.S.A.; **Rodney L. Anderson**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Demands on numerical integration algorithms for astrodynamics applications continue to increase. Common methods, like explicit Runge-Kutta, meet the orbit propagation needs of most scenarios, but more specialized scenarios require new techniques to meet both computational efficiency and accuracy needs. This paper provides an extensive survey on the application of symplectic and collocation methods to astrodynamics. Both of these methods benefit from relatively recent theoretical developments, which improve their applicability to artificial satellite orbit propagation. This paper also details their implementation, with several tests demonstrating their advantages and disadvantages. [View Full Paper]

AAS 12 – 215

Appropriate Modeling of Solar Radiation Pressure Effects on Uncontrolled Orbiting Objects for Accurate Dynamical Predictions

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

In this paper, we investigate the 6 degree-of-freedom motion of various objects perturbed by solar radiation pressure (SRP) forces and torques. Particular emphasis is placed on the investigation of the attitude dynamics of these objects, as this component has typically been ignored in the literature associated with solar radiation pressure effects in favor of using the classical cannonball model which produces no torques. There are three main contributions. First, an averaged torque was derived for a uniformly tumbling objects which shows that the torque only disappears on average for a optically uniform sphere; any other shape will be torqued on average by SRP. The second contribution is an illustration of the importance of accounting for self-shadowing when considering non-convex bodies. Third, simulations are used to show that for many different situations, the cannonball model is inappropriate to accurately capture the effects of SRP on a bodies orbit and attitude evolution. [View Full Paper]

AAS 12 – 216

A New Numerical Integration Technique in Astrodynamics

Ben K. Bradley, **Brandon A. Jones**, **Gregory Beylkin** and **Penina Axelrad**,
University of Colorado at Boulder, Colorado, U.S.A.

This paper describes a new method of numerical integration and compares its efficiency in propagating orbits to existing techniques commonly used in astrodynamics. By using generalized Gaussian quadratures for bandlimited functions, the implicit Runge-Kutta scheme (a collocation method) allows us to use significantly fewer force function evaluations than other integrators. The new method computes the solution on a large time interval, leading to a different approach to force evaluation. In particular, it is sufficient to use a low-fidelity force model for most of the iterations, thus minimizing the use of a high-fidelity force model. Our goal is to develop a numerical integration technique that is faster than current methods in an effort to address the expected increase of the space catalog due to improvements in tracking capabilities.
[View Full Paper]

AAS 12 – 217

Perturbation and Stability Analysis of Displaced, Geostationary Orbits Using Computational and Analytical Techniques

Andrew Rogers, **Ryan Stanley** and **Troy Henderson**, Department of Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

Recent research on trajectory design using low-thrust propulsion has opened up new avenues in orbital mechanics. One application is the displaced, geostationary orbit. A displaced orbit will afford the stationary component of a geostationary orbit, but in a noncrowded environment, as well provide the spacecraft with higher latitudes of continuous coverage, opening new opportunities in geospace science and communications. The equations of motion for this orbit are highly nonlinear, but there is a defined stability below which a satellite will be able to maintain station when perturbed, and above which the orbit will degrade. Specific perturbations will be analyzed for linearized cases and then verified numerically. [View Full Paper]

AAS 12 – 218

Comparison of Delaunay Normalization and the Krylov-Bogoliubov-Mitropolsky Method

Juan F. San-Juan, **Luis M. López** and **David Ortigosa**, Universidad de La Rioja, Logroño, Spain; **Martín Lara**, TENECO, Logroño, Spain; **Paul J. Cefola**, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

A scalable second-order analytical orbit propagator program (AOPP) is being carried out. This AOPP combines modern and classical perturbation methods in function of orbit types or the requirements needed for a space mission, such as catalog maintenance operations, long period evolution, and so on. As a first step on the validation and verification of part of our AOPP, we only consider perturbation produced by zonal harmonic coefficients in the Earth's gravity potential, so that it is possible to analyze the behavior of the mathematical expression involved in the corresponding analytical theory in depth and determine its limits. [View Full Paper]

AAS 12 – 219

Detailed Analysis of Solar and Thermal Accelerations on Deep-Space Satellites

Takahiro Kato, **Benny Rievers** and **Claus Laemmerzahl**; Center for Applied Space Technology and Microgravity, ZARM, University of Bremen, Bremen, Germany; **Jozef C. van der Ha**, Consultant, Spacecraft Design and Operations, Bensheim, Germany

This paper presents novel generic analytical and numerical approaches for modeling the Solar Radiation Pressure and Thermal Recoil Pressure effects for high accuracy mission applications. High fidelity is achieved by taking account of the detailed spacecraft model and the operational history of the high-gain antenna articulations as well as the spacecraft attitude pointing. Both analytical and numerical approaches are applied in full detail to ESA's current deep-space mission Rosetta during its cruise phases. The validity of those two Solar Radiation Pressure models is established by comparison with respect to ESOC's software predictions. In addition, the contributions of the Thermal Recoil Pressure effects are evaluated. [View Full Paper]

AAS 12 – 220
(Paper Withdrawn)

SESSION 16: ASTEROID AND NEAR-EARTH OBJECT MISSIONS II
Chair: Dr. Roby Wilson, Jet Propulsion Laboratory

AAS 12 – 221

Imaging LIDAR Mapping of Asteroids for Onboard Autonomy of Scout Spacecraft

Brandon Marsella, **Bogdan Udrea** and **Parv Patel**, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.; **Paul Anderson**, University of Colorado at Boulder, Colorado, U.S.A.

In order to decrease the risk of landing on an asteroid, a Light Detection and Ranging (LIDAR) system can be utilized. While in orbit the imaging LIDAR will generate a theoretically more detailed shape model than one which can be developed from Earth based observations. Using this model a more accurate gravitation field model can be generated on board by using a variable sphere method, and thus better landing trajectories can be determined.

The LIDAR mapping phase of the autonomous proximity operations of an asteroid scout spacecraft is analyzed for the purpose of specifying requirements for the guidance navigation and control subsystem of the spacecraft, identify performance metrics for on-board autonomy, and develop navigation and mapping algorithms. The long term goal is to integrate the sensor models and the algorithms into an onboard autonomy architecture controlled by a system such as Jet Propulsion Laboratory's Continuous Activity Scheduling Planning Execution and Replanning (CASPER). [View Full Paper]

AAS 12 – 222

Sensitivity Analysis of the Touchdown Footprint at (101955) 1999 RQ_{36}

Bogdan Udrea and **Parv Patel**, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.; **Paul Anderson**, University of Colorado at Boulder, Colorado, U.S.A.

This paper describes the analysis of the touchdown footprint of an asteroid sample return mission. The mission bears similarity with NASA's Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission. The target asteroid is (101955) 1999 RQ_{36} and the spacecraft mass and overall dimensions are similar to those of OSIRIS-REx. A shape model of (101955) 1999 RQ_{36} is employed to create three gravitational models of the asteroid and the models are analyzed in order to select the model that gives good accuracy with the least computational effort. A stable, retrograde orbit, in the plane of the terminator, of 1.5 km radius, is designed and shown to be bound for about 25 days. The descent trajectory, also called the touch-and-go profile, starts from the home orbit and takes the spacecraft to asteroid touchdown by employing three maneuvers. The maneuvers are designed with a Lambert's problem solver so that the first transfer arc is on an elliptic orbit with a periapsis altitude of 20 m and the nominal touchdown speed is 0.1 m/s. For this analysis the target touchdown spot is on the equator of the asteroid at 44°E longitude. The size and orientation of the touchdown footprint are determined using a Monte Carlo analysis that assumes that the off-nominal and uncertain parameters for the asteroid and spacecraft are normally distributed. The resulting 3σ ellipse, projected on a mean sphere of 287.5 m radius, has a semimajor axis of 115 m and a semiminor axis of 16 m. [View Full Paper]

AAS 12 – 223

Refined Gravity Determination at Small Bodies through Landing Probes

Julie Bellerose, Carnegie Mellon University SV / NASA ARC, NASA Ames Research Center, Moffet Field, California, U.S.A.

Very small near Earth objects are among the small body populations not yet visited to date, while providing a pool of low-cost targets for science and exploration objectives. Current mass determination techniques involve determining the deflection of the asteroid trajectory when flying by other asteroids and planets, or tracking of a spacecraft as it is either flying by the asteroid target or is in orbit about it. Spacecraft orbit determination at very small asteroids involves large error due to distances involved and the very low attractive pull from the bodies. This results in higher error on mass and bulk density estimation, and can affect subsequent operation planning. We investigate the constraints at very small near Earth Objects, and an additional mean for mass measurement using landing probes. The landing dynamics can be retrieved from relative motion with the spacecraft. We show analytical methods to estimate the performance and constraints for given mission design, simulations, and mission concepts to measure and refine the mass and local density at small bodies with diameter less than 100 m using probes released from a spacecraft. [View Full Paper]

AAS 12 – 224

Surface Gravity Fields for Asteroids and Comets

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

In this paper, we derive and summarize the characteristics of the interior gravity field and evaluate its performance near the surface of an asteroid for the purpose of small body proximity operations. The exterior potential is widely in use to characterize the gravity field of a body, and it is particularly suitable for a body in a nearly spherical shape. However, the exterior gravity field expression breaks down when computing the potential and its gradients within the Brillouin sphere, meaning that spacecraft dynamics cannot be modeled accurately in close proximity to the body's surface. On the other hand, the convergence of the potential and its gradients are guaranteed within the Brillouin sphere of the interior potential, a feature that makes the interior gravity field a good candidate for modeling the gravity field environment near the surface of a body. We summarize the original derivation by Werner,1 outline the techniques for converting an exterior gravity field or a polyhedral shape model gravity field into an interior gravity field, compare the spacecraft dynamics propagated in the exterior/interior gravity fields, and introduce a method to numerically approximate the interior spherical harmonics for a body with a homogeneous density distribution. Our results show that the interior gravity field models the gravity field environment well in close proximity to the body's surface. [View Full Paper]

AAS 12 – 225

Preliminary Design of a Hypervelocity Nuclear Interceptor System (HNIS) for Optimal Disruption of Near-Earth Objects

Alan Pitz, **Brian Kaplinger** and **Bong Wie**, Asteroid Deflection Research Center, Iowa State University, Ames, Iowa, U.S.A.; **David Dearborn**, Lawrence Livermore National Laboratory, Livermore, California, U.S.A.

When the warning time of an Earth-impacting NEO is short, the use of a nuclear explosive device (NED) may become necessary to optimally disrupt the target NEO in a timely manner. In this situation, a rendezvous mission becomes impractical due to the resulting NEO intercept velocity exceeding 10 km/s. Because the conventional penetrating NEDs require the impact speed to be less than 300 m/s, an innovative concept of blending a hypervelocity kinetic impactor with a subsurface nuclear explosion has been proposed for optimal penetration, fragmentation, and dispersion of the target NEO. A proposed hypervelocity nuclear interceptor system (HNIS) consists of a kinetic-impact leader spacecraft and a follower spacecraft carrying NEDs. This paper describes the conceptual development and design of an HNIS, including thermal shielding of a follower spacecraft, targeting sensors and optical instruments of a leader spacecraft, terminal guidance propulsion systems, and other secondary configurations. Simulations using a hydrodynamic code are conducted to calculate the optimal separation distance between the two vehicles and the thermal and structural limitations encountered by the follower spacecraft carrying NEDs. [View Full Paper]

AAS 12 – 226

Optimal Target Selection for a Planetary Defense Technology (PDT) Demonstration Mission

Tim Winkler, **Sam Wagner** and **Bong Wie**, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

During the past two decades, various options such as nuclear explosions, kinetic impactors, and slow-pull gravity tractors have been proposed for mitigating the impact threat of near-Earth objects (NEOs). However, currently, there is no consensus on how to reliably deflect or disrupt hazardous NEOs in a timely manner. The use of nuclear explosives may become inevitable for the most probable impact threat with a short warning time. This paper presents potential NEO candidates selected for a planetary defense technology (PDT) demonstration mission, currently being envisioned by the planetary defense community. A flight demonstration mission is necessary to validate and verify the practical effectiveness of blending a hypervelocity kinetic impactor with a penetrated nuclear subsurface explosion. [View Full Paper]

AAS 12 – 227

The SIROCO Asteroid Deflection Demonstrator

Claudio Bombardelli and **Hodei Urrutxua**, Space Dynamics Group, Technical University of Madrid (UPM), Madrid, Spain;
Andres Galvez and **Ian Carnelli**, European Space Agency, Paris, France

There is evidence of past Near-Earth-Objects (NEOs) impacts on Earth and several studies indicating that even relatively small objects are capable of causing large local damage, either directly or in combination with other phenomena, e.g. tsunamis. This paper describes a space mission concept to demonstrate some of the key technologies to rendezvous with an asteroid and accurately measure its trajectory during and after a deflection maneuver. The mission, called SIROCO, makes use of the recently proposed ion beam shepherd (IBS) concept where a stream of accelerated plasma ions is directed against the surface of a small NEO resulting in a net transmitted deflection force. We show that by carefully selecting the target NEO a measurable deflection can be obtained in a few weeks of continuous thrust with a small spacecraft and state of the art electric propulsion hardware. [View Full Paper]

AAS 12 – 228

Validation and Application of a Preliminary Target Selection Algorithm for the Design of a Near Earth Asteroid Hopping Mission

Michael V. Nayak, Space Development and Test Directorate, United States Air Force, Albuquerque, New Mexico, U.S.A.; **Bogdan Udrea**, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.

A prospecting mission with a human crew on board is planned to visit multiple near-Earth asteroids (NEAs); the number of NEAs visited is maximized across a mission timeline limited at three years with a minimum operations time at any NEA of five days. The paper describes the setup and results of an algorithm employed for preliminary asteroid target selection for the mission. The algorithm is used to determine the order of transfer between viable targets, keeping ΔV at a minimum, minimizing the computational burden of optimization and maximizing the number of targets visited within the mission timeline. Based on distance from the originating asteroid, inclination change, and planetary perturbation effects, the algorithm is used to support a decision-tree approach to target selection. Results are validated using Satellite Tool Kit v.9.1 Design Explorer Optimizer and used to plan a five-asteroid mission.
[View Full Paper]

SESSION 17: TRAJECTORY OPTIMIZATION II
Chair: Dr. Ryan Russell, University of Texas at Austin

AAS 12 – 229
(Paper Withdrawn)

AAS 12 – 230

Integrated Launch Window Analysis and Precision Transfer Trajectory Design for Mars Missions

Zhong-Sheng Wang, **Melissa H. Gambal** and **Natalie A. Spencer**, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.; **Paul V. Anderson**, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Colorado, U.S.A.; **Robert Hook**, Institut für Luft- und Raumfahrt, Technische Universität Berlin, Berlin, Germany

Iterative procedures may not converge when linear corrections are applied in precision transfer trajectory design for interplanetary missions. It has been shown that using multiple linear corrections can solve this problem effectively. This paper proposes a more efficient multiple linear correction scheme that leads to faster convergence. Also discussed is the important practical issue of integrating launch window analysis and precision transfer trajectory design for Mars missions. It is shown that an iterative procedure can be used to resolve this issue effectively. This work and the author's previous work constitute a complete theory of conventional transfer trajectory design for Mars missions. [View Full Paper]

AAS 12 – 231

Iterative Model Refinement for Orbital Trajectory Optimization

Jennifer Hudson and **Ilya Kolmanovsky**, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.

In this paper, an iterative model and trajectory refinement (IMTR) method is applied to spacecraft trajectory optimization. A high-fidelity model and a low-fidelity model are used to iteratively refine solutions. The high-fidelity model accurately represents the system but is not easily amenable to trajectory optimization, due to high computational cost or due to being of "black-box" type (e.g. Jacobian cannot be easily computed or the state is not easily accessible). The low-fidelity model is suitable for numerical optimization, but approximates the system dynamics with an unknown error. An iterative model and trajectory refinement method is proposed to systematically iterate between the two models and converge on a solution with efficient execution time.
[View Full Paper]

AAS 12 – 232
(Paper Withdrawn)

AAS 12 – 233
(Paper Withdrawn)

AAS 12 – 234

Optimal Solar Sail Trajectory Analysis for Interstellar Missions

Xiangyuan Zeng and **Junfeng Li**, School of Aerospace, Tsinghua University, Beijing, China; **Kyle. T. Alfriend** and **S. R. Vadali**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

The optimization of an interstellar probe trajectory using a relatively mid performance solar sail is investigated for a single solar photonic assistance. With an approach to a minimum solar distance away from the Sun, solar sails can enable the sailcraft gain high energy to escape the solar system with a cruise speed of greater than 10 AU/year. Based on a reasonable assumption of a jettison point at 5 AU, a new objective function with a variable scale parameter is adopted to solve the time optimal control problem using an indirect method. In this paper the problem is addressed for an ideal flat sail in the two-body problem. A technique of scaling of the adjoint variables is presented to make the optimization much easier than before. A comparison between the current results and previous studies has been conducted to show the advantages of the new objective function. In terms of the mission time, the influence of the departure point of the sailcraft from the Earth orbit is discussed without consideration of the Geo-centric escape phase, which can be completed by various means. Another interesting discovery is that the angular momentum reversal trajectory is also achieved as a local-optimal solution in a demonstration mission of 250AU. Under the same initial condition, the difference between the two types of solar escape trajectories is discussed in detail through numerical simulations along with the advantages. [View Full Paper]

AAS 12 – 235

Optimal Use of Perturbations for Space Missions

Francesco de Dilectis and **Daniele Mortari**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

In this study we try to use orbital perturbations as an aid in orbital maneuvers. This idea is certainly not new, and has been applied in the past, especially limited to the J_2 effect on the RAAN and argument of perigee. However, here the idea is taken much further, and the combined effect of many different perturbations is taken into account. To achieve this, a propagator based on the SGP4 method is used. Each orbit can be considered a point in a 6-dimensional space, and each can be propagated either backward or forward in time to determine a trajectory in such hyperspace; the method proposed here, given a starting and final orbits, propagates them both in time, respectively forward and backward, and then, via a genetic algorithm set to minimize the total ΔV, finds the optimal points along the propagated trajectories to apply impulses and connect the two. This can be adapted to use more than 2 impulses and to solve rendezvous problems also. Possible applications range from simple improvement on the classical transfer maneuvers, to entirely new techniques studied for instance to deploy satellites belonging to the same constellation. [View Full Paper]

AAS 12 – 236

Recent Improvements to the Copernicus Trajectory Design and Optimization System

Jacob Williams, ERC, Inc. (Engineering and Science Contract Group), Houston, Texas, U.S.A.; **Juan S. Senent**, Odyssey Space Research, Houston, Texas, U.S.A.;
David E. Lee, EG/Aeroscience and Flight Mechanics Division, NASA Johnson Space Center, Houston, Texas, U.S.A.

Copernicus is a software tool for advanced spacecraft trajectory design and optimization. The latest version (v3.0.1) was released in October 2011. It is available at no cost to NASA centers, government contractors, and organizations with a contractual affiliation with NASA. This paper provides a brief overview of the recent development history of Copernicus. An overview of the evolution of the software is given, along with a discussion of significant new features and improvements (such as gravity assist maneuvers, halo orbits, and a new impulsive to finite burn conversion wizard). Some examples of how Copernicus is used to design spacecraft missions are also shown.
[View Full Paper]

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

AAS 12 – 237
Spacecraft Attitude Stabilization Using Nonlinear Delayed Actuator Control with an Inverse Dynamics Approach

Morad Nazari, **Ehsan Samiei** and **Eric A. Butcher**, Mechanical and Aerospace Engineering Department, New Mexico State University, Las Cruces, New Mexico, U.S.A.; **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

The dynamics of a rigid body with nonlinear delayed feedback control are studied in this paper. It is assumed that the time delay occurs in one of the actuators while the other one remains is delay-free. Therefore, a nonlinear feedback controller using both delayed and non-delayed states is sought for the controlled system to have the desired linear closed-loop dynamics which contains a time-delay term using an inverse dynamics approach. First, the closed-loop stability is shown to be approximated by a second order linear delay differential equation (DDE) for the MRP attitude coordinate for which the Hsu-Bhatt-Vyshnegradskii stability chart can be used to choose the control gains that result in a stable closed-loop response. An analytical derivation of the boundaries of this chart for the undamped case is shown, and subsequently the Chebyshev spectral continuous time approximation (ChSCTA) method is used to obtain the stable and unstable regions for the damped case. The MATLAB `dde23` function is implemented to obtain the closed-loop response which is in agreement with the stability charts, while the delay-free case is shown to agree with prior results. [View Full Paper]

AAS 12 – 238
Backstepping Simple Adaptive Control and Disturbance Rejection for Spacecraft with Unmodeled Dynamics

Min Liu, **Hong Guan**, **Shijie Xu** and **Chao Han**, School of Astronautics, Beihang University, Beijing, China

The attitude tracking control problem of spacecraft with unmodeled dynamics and persistent disturbances is studied in this paper. Based on backstepping control algorithm, a nonlinear backstepping simple adaptive controller (BSAC) and a nonlinear backstepping simple adaptive disturbance rejection (BSADR) controller are derived for spacecraft. In order to apply the proposed controllers, the spacecraft system is divided into a dynamics subsystem and a kinematics subsystem, and only the linear part of the dynamics subsystem is required to be Almost Strict Positive Real (ASPR). Firstly, the angular velocity is selected as the intermediate control vector and a constant feedback intermediate control law is designed to stabilize the kinematics subsystem. Then backing a step, using backstepping method, nonlinear simple adaptive control method, the proposed controllers are derived, and the stabilities of these controllers are proved by Lyapunov method. Finally, numerical examples are studied to validate the efficiency of the proposed controllers. [View Full Paper]

AAS 12 – 239

Hybrid Method for Constrained Time-Optimal Spacecraft Reorientation Maneuvers

Robert G. Melton, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.

Time-optimal spacecraft slewing maneuvers with path constraints are difficult to compute even with direct methods. This paper examines the use of a hybrid, two-stage approach, in which a particle swarm optimizer provides a rough estimate of the solution, and that serves as the input to a pseudospectral optimizer. Performance is compared between a particle swarm optimizer and a differential evolution optimizer in the first stage. [View Full Paper]

AAS 12 – 240

Laboratory Experiments for Position and Attitude Estimation Using the Cayley Attitude Technique

Kurt A. Cavalieri, **Brent Macomber** and **John E. Hurtado**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.;
Manoranjan Majji, Department of Mechanical and Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

Single point attitude determination is the problem of estimating the instantaneous attitude of a rigid body from a collection of vector observations taken at a single moment in time. A new attitude estimation technique uses a generalized Cayley transform and finds algorithms to optimally solve the attitude estimation problem for a wide family of attitude parameters. The four dimensional Cayley attitude technique provides an elegant solution to the single point position and attitude estimation problem. Robustness of this technique in the presence of noise is tested through experiments at the Land, Air, and Space Robotics Laboratory. [View Full Paper]

AAS 12 – 241

Projective Geometry of Attitude Parameterizations with Applications to Estimation

Sergei Tanygin, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

Vectorial attitude parameterizations, defined as products of the unit axis of rotation and various functions of the rotation angle, can be viewed as projections from the unit quaternion hypersphere onto a hyperplane tangential to this hypersphere. It is shown how additive and multiplicative errors can be geometrically interpreted using projective geometry of vectorial parameterizations. It is then shown how they can be used to model errors in vector and angle observations. It is also shown how these errors can be propagated using variational equations derived and analyzed in the general form. The effect of specific generating functions of the rotation angle on the attitude error propagation is examined. Finally, it is shown how projective geometry can be used to update quaternion averaging so that it agrees more closely with the geodesic mean.
[View Full Paper]

AAS 12 – 242

Under-Actuated Moving Mass Attitude Control for a 3U Cubesat Mission

Brad M. Atkins and **Troy A. Henderson**, Department of Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

A 3 Unit cubesat mission is under development at Virginia Tech with a launch date set within the next two years. An internal, moving mass linear actuator system is under consideration for the attitude control mechanisms. For the under-actuated (2 mass actuators) configuration, full rotational dynamics about the instantaneous center of mass are presented followed by an approximate formulation useful for linear control development, applicable for zero initial angular momentum and negligible environmental torques. MATLAB numerical simulations of the full rotational dynamics have demonstrated that for low mass weights (mass <1/10 payload mass) and low mass extension rates, (rates <2 cm/ sec) periodic combinations of the two actuators can produce net yaw, pitch, and roll of a cubesat configured comparably to the actual planned mission. For the external torque-free case, three separate periodic mass motion profiles are presented that can respectively yaw, pitch and roll the cubesat. For the mass actuator configuration presented, large yaw reorientation can be achieved with few mass motion intervals. This sensitivity arises from the yaw axis being perpendicular to the plane of the mass actuators. Such initial results suggest the efficacy of mass attitude control systems (both fully and under-actuated) may have wide application including application to space telescope attitude control systems, satellite control, and re-entry vehicle control.
[View Full Paper]

AAS 12 – 243

Using Kane's Method to Incorporate Attitude Dynamics in the Circular Restricted Three Body Problem

Amanda J. Knutson and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

The model framework developed in this investigation yields the fully coupled equations of motion that govern orbital motion and spacecraft orientation within the context of the circular restricted three body problem. The motion of a spacecraft, composed of two rigid bodies connected by a single degree of freedom joint, is examined. The nonlinear variational form of the equations of motion is employed to mitigate numerical effects caused by large discrepancies in the length scales. Several nonlinear, planar, periodic reference orbits in the vicinity of the collinear libration points are selected as case studies and the effects of the orbit on the orientation, and orientation on the orbit are examined. [View Full Paper]

AAS 12 – 244

Using the Magnetospheric Multiscale (MMS) Tablesat IB for the Analysis of Attitude Control and Flexible Boom Dynamics for MMS Mission Spacecraft

Timothy John Roemer, **Nicholas F. Aubut**, **Joshua Chabot**, **William K. Holmes**, **Abigail Jenkins**, **Michael Johnson** and **May-Win L. Thein**, Mechanical Engineering Department, University of New Hampshire, Durham, New Hampshire, U.S.A.

The NASA Magnetospheric Multiscale (MMS) Mission consists of four spin-stabilized spacecraft (s/c) flying in precise formation. To analyze the 60 meter, wire thin booms on the MMS s/c and the s/c overall dynamics, a series of table top prototypes are developed. In this paper, the authors present the MMS TableSat IB, a limited 3-DOF rotation (full spin, limited nutation) tabletop test bed of theMMS s/c, which is an improved prototype over that of the original TableSat I. The primary focus of this stage of research is to observe the effects of spin rate control on s/c dynamics, particularly with regards to flexible boom dynamics. An analytical model of the system is first obtained and a bang-bang controller is implemented to mimic the TableSat IB's pneumatic thrust system. When applied to the MMS s/c prototype, it is found that the flexible booms have a pronounced effect on the dynamics of the model s/c and on the effectiveness of the binary controller. [View Full Paper]

SESSION 19: ORBITAL DEBRIS

Chair: Dr. Thomas Starchville, The Aerospace Corporation

AAS 12 – 245

An Orbital Conjunction Algorithm Based on Taylor Models

R. Armellin, **P. Di Lizia**, **A. Morselli** and **M. Lavagna**, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Milano, Italy

The study of orbital conjunctions between space bodies is of fundamental importance in space situational awareness programs. The identification of potentially dangerous conjunctions, either between Near Earth Objects and our planet, or space debris and operative spacecraft, is most commonly done by looking at the distance between the objects in a given time window. A method based on Taylor models and Taylor differential algebra is presented to compute the time and distance of closest approach and to assess the effect that uncertainties on initial orbital parameters produce on these quantities. [View Full Paper]

AAS 12 – 246

Relative Dynamics and Control of an Ion Beam Shepherd Satellite

Claudio Bombardelli, **Hodei Urrutxua** and **Jesús Peláez**, Space Dynamics Group, Technical University of Madrid, Madrid, Spain; **Mario Merino** and **Eduardo Ahedo**, Plasma and Space Propulsion Group, Technical University of Madrid, Madrid, Spain

The ion beam shepherd (IBS) is a recently proposed concept for modifying the orbit and/or attitude of a generic orbiting body in a contactless manner, which makes it a candidate technology for active space debris removal. In this paper we deal with the problem of controlling the relative position of a shepherd satellite coorbiting at small separation distance with a target debris. After deriving the orbit relative motion equations including the effect of the ion beam perturbation we study the system stability and propose different control strategies. [View Full Paper]

AAS 12 – 247

Including Velocity Uncertainty in the Probability of Collision between Space Objects

Vincent T. Coppola, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

While there has been much research on computing the probability of collision between space objects, there is little work on incorporating velocity uncertainty into the computation. We derive the formula from first principles, including both position and velocity uncertainty. Moreover, trajectories will evolve according to differential equations and not by approximating the relative motion. The end result is a 3-dimensional integral over time on the surface of a sphere. We show that the formula recovers the classic formula in the limit as the velocity uncertainty approaches zero. Finally, the results produced using the new formula will be compared to the results of Monte Carlo simulations. [View Full Paper]

AAS 12 – 248

Evaluating the Short Encounter Assumption of the Probability of Collision Formula

Vincent T. Coppola, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

The formula for the probability of collision for space objects results from many assumptions concerning the motion of the objects, not least of which is that the encounter duration is short. We develop a formula that characterizes the encounter duration for the conjunction of two space objects and then compute it for every conjunction in an all-on-all assessment of the public catalog. We then introduce the concept of a short-term encounter validity interval that characterizes the total encounter time under which the short-term assumptions are assumed met. This metric provides the means for assessing whether a conjunction satisfies the short encounter assumption so that the standard collision probability metric is valid. [View Full Paper]

AAS 12 – 249

Lambert Targeting for on-Orbit Delivery of Debris Remediation Dust

Liam M. Healy, U.S. Naval Research Laboratory, Washington, D.C., U.S.A.

Rapid delivery of material on-orbit (without regard to final velocity) is possible by pre-positioning on orbit a vehicle with the intended cargo. If the goal is to reach a specified point in inertial space to precede the return of another vehicle to that point using Lambert targeting, and there is a limit to the amount of delta-v available, then certain orbits are better choices than others. In the context of dispensing a dust to enhance drag for elimination of debris, I examine the combination of vehicles which gives the most coverage to treat the most populous altitude band of satellites. [View Full Paper]

AAS 12 – 250

Spacecraft Debris Avoidance Using Positively Invariant Constraint Admissible Sets

Morgan Baldwin and **R. Scott Erwin**, Space Vehicles Directorate, Air Force Research Laboratory, Albuquerque, New Mexico, U.S.A.;
Avishai Weiss and **Ilya Kolmanovsky**, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.

To cope with the growing amount of debris in the Earth orbit, spacecraft collision avoidance capabilities are necessary. In this paper, we propose an approach to debris avoidance maneuvering based on the use of safe positively invariant sets in order to steer the spacecraft, under closed-loop control, around a piece of debris. A connectivity graph of forced equilibria is computed based on the overlap of these invariant sets, and a graph search algorithm is then implmented in order to find the shortest path around the debris. Fast growth distance computation is employed for on-board real-time applicability. Simulation results are presented that illustrate this approach. [View Full Paper]

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(Paper Withdrawn)

AAS 12 – 252

Tethered Tug for Large Low Earth Orbit Debris Removal

Lee E. Z. Jasper, **Carl R. Seubert** and **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.;
Valery Trushkyakov and **Evgeny Yutkin**, Department of Aviation and Rocket Building, Omsk State Technical University, Omsk, Russia

The low Earth orbit debris environment continues to be a concern for the space community. While debris mitigation is an important component of reducing on-orbit clutter, active debris removal methods are likely to be necessary in the future. A debris removal system is proposed which uses fuel reserves from the second stage of a heavy launch vehicle after it has delivered its primary payload. Upon tethering to a large debris object such as another second stage rocket body, a Δv maneuver is performed to lower both objects' periapses. Specifically, a Soyuz-like rocket-body is considered the thrusting tug craft, while a Cosmos-3M rocket-body is considered the debris object. The Cosmos-3M is found to most densely populate the orbits around 700 km - 900 km between 83° and 98° declination. To deorbit a Cosmos-3M in 25 years from an 800 km orbit only requires a combined Δv = 120 m/s. This is within the fuel reserve budget of the Soyuz upper stage. To provide insight into the tug-debris dynamics, the tether is modeled as a spring with rigid body end masses while the tether is in tension. In order to avoid collision between the two craft, deep-space dynamics reveal that the thrust can be throttled in synchronization with the relative motion so that, at the end of a burn, zero relative velocity between the two craft is achieved. The on-orbit dynamics reveal that the orbital motion helps keep both craft separated. Further, low-thrust applications, or large initial separation distance, are shown to reduce the likelihood of post-burn collisions. [View Full Paper]

SESSION 20: EARTH ORBITAL MISSIONS
Chair: Dr. Xiaoli Bai, Texas A&M University

AAS 12 – 253
APCHI Technique for Rapidly and Accurately Predicting Multi-Restriction Satellite Visibility

Xiucong Sun and **Chao Han**, School of Astronautics, Beihang University, Beijing China; Hongzheng Cui and **Geshi Tang**, Flight Dynamics Laboratory, Beijing Aerospace Control Center, Beijing, China

Multi-Restriction Satellite Visibility Prediction (MRSVP) problem is of great significance in space missions such as Earth observation and space surveillance. This paper presents a numerical method to rapidly and accurately compute site-satellite and satellite-satellite in-view periods, taking multiple restrictions into account. A novel curve fitting method named Adaptive Piecewise Cubic Hermite Interpolation (APCHI) technique is introduced to approximate waveforms of visibility functions derived for corresponding restrictions, featured with autonomous searching for the best interpolation points to guarantee accuracy. Test results obtained from this approach are almost the same with those from conventional trajectory check method. However, this new approach reduces more than 90% of computation time. As this numerical method can apply to all kinds of orbit types and propagators, it proves to be a good choice for satellite constellation design and mission planning. [View Full Paper]

AAS 12 – 254
Landsat Data Continuity Mission (LDCM) Ascent and Operational Orbit Design

Laurie M. Mann, **Ann M. Nicholson** and **Susan M. Good**, Mission Services Division, a.i. solutions Inc., Lanham, Maryland, U.S.A.; **Mark A. Woodard**, Navigation and Mission Design Branch, NASA GSFC, Greenbelt, Maryland, U.S.A.

For the past 40-years, Landsat Satellites have collected Earth's continental data and enabled scientists to assess change in the Earth's landscape. The Landsat Data Continuity Mission (LDCM) is the next generation satellite supporting the Landsat science program. LDCM will fly a 16-day ground repeat cycle, Sun-synchronous, frozen orbit with a mean local time of the descending node ranging between 10:10 am and 10:15 am. This paper presents the preliminary ascent trajectory design from the injection orbit to its final operational orbit. The initial four burn ascent design is shown to satisfy all the LDCM mission goals and requirement and to allow for adequate flexibility in re-planning the ascent. [View Full Paper]

AAS 12 – 255

Launch Window Analysis for the Magnetospheric Multiscale Mission

Trevor Williams, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

The NASA Magnetospheric Multiscale (MMS) mission will fly four spinning spacecraft in formation in highly elliptical orbits to study the magnetosphere of the Earth. This paper describes the development of an MMS launch window tool that uses the orbit-averaged Variation of Parameter equations as the basis for a semi-analytic quantification of the dominant oblateness and lunisolar perturbation effects on the MMS orbit. This approach, coupled with a geometric interpretation of all of the MMS science and engineering constraints, allows a scan of 180^2 = 32,400 different (RAAN, AOP) pairs to be carried out for a specified launch day in less than 10 s on a typical modern laptop. The resulting plot indicates the regions in (RAAN, AOP) space where each constraint is satisfied or violated: their intersection gives, in an easily interpreted graphical manner, the final solution space for the day considered. This tool, SWM76, is now used to provide launch conditions to the full fidelity (but far slower) MMS simulation code: very good agreement has been observed between the two methods. [View Full Paper]

AAS 12 – 256

Two Geometric Aspects of the Orbiting Carbon Observatory 2 Mission

Mark A. Vincent, Navigation and Mission Design, Raytheon, Pasadena, California, U.S.A.

Two completely separate analyses will be presented in this paper. They both have been performed in support of the re-flight of the Orbiting Carbon Observatory (OCO-2). The first involves the location that the mission has been allocated at the front of the A-Train. The geometry involved in safely staying in front of JAXA's soon-to-be-launched GCOM-W1 while avoiding the tail of the Morning Constellation will be described. The other analysis involves the geometry in obtaining the OCO-2 measurements while in Glint Mode. The algorithms for calculating the Glint Spot on a smooth sphere and an ellipsoid will be described and compared. [View Full Paper]

AAS 12 – 257

Static Highly Elliptical Orbits Using Hybrid Low-Thrust Propulsion

Pamela Anderson and **Malcolm Macdonald**, Advanced Space Concepts Laboratory, University of Strathclyde, Glasgow, Scotland, E.U.

The use of extended static-highly elliptical orbits, termed Taranis orbits, is considered for continuous observation of high latitude regions. Low-thrust propulsion is used to alter the critical inclination of Molniya-like orbits to any inclination required to optimally fulfill the mission objectives. This paper investigates a constellation of spacecraft at *90deg* inclination for observation of latitudes beyond *55deg* and *50deg*, considering: spatial resolution, radiation environment, number of spacecraft and End of Life debris mitigation measures. A constellation of four spacecraft on a 16-hr Taranis orbit is identified to enable continuous observation to *55deg* latitude. Neglecting constraints to minimize the radiation allows the number of spacecraft in the constellation to be reduced to three on a 12-hr orbit. Similarly to view continuously to *50deg*, eight spacecraft on a 16-hr orbit are required; this is reduced to five neglecting radiation constraints. It is anticipated that it is significantly more cost effective to reduce the number of required launches and employ additional radiation shielding. Thus, a constellation of three or five spacecraft on the 12-hr Taranis orbit is considered the most beneficial when observing to latitudes of *55deg* and *50deg* respectively. Hybrid solar sail / Solar Electric Propulsion systems are considered to enable the Taranis orbits, where the acceleration required is made up partly by the acceleration produced by the solar sail and the remainder supplied by the electric thruster. Order of magnitude mission lifetimes are determined, a strawman mass budget is also developed for two system constraints, firstly spacecraft launch mass is fixed, and secondly the maximum thrust of the thruster is constrained. Fixing mass results in negligible increases in mission lifetimes for all hybrid cases considered, solar sails also require significant technology development. Fixing maximum thrust of the electric thruster increases mission lifetime and solar sails are considered near to mid-term technologies. This distinction highlights an important contribution to the field, illustrating that the addition of a solar sail to an electric propulsion craft can have negligible benefit when mass is the primary system constraint. Technology requirements are also outlined, including sizing of solar arrays, electric thruters, propellant tanks and solar sails. [View Full Paper]

AAS 12 – 258

Sun-Synchronous Orbit Slot Architecture: Analysis and Development

Eric Watson and **Kira Abercromby**, Aerospace Engineering Department, California Polytechnic State University, San Luis Obispo, California, U.S.A.;
T. Alan Lovell, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

Growing concern over the space debris issue as well as a possible influx in space traffic will create a need for increased space traffic management. Currently, an orbital slot framework is internationally agreed upon for geostationary satellites. Due to its population density and likely future growth, Sun-synchronous orbit is the next logical orbit regime to apply a slot architecture. This paper furthers work done in Sun-synchronous orbit slot architecture design by accomplishing in-depth relative motion analysis of satellites with respect to their assigned slots. A strategy is presented for developing a useful slot architecture that does not impose unreasonable satellite design requirements. [View Full Paper]

AAS 12 – 259

Preliminary Design for a Mini-Satellite for Drag Estimation (MINDE)

David Armstrong, **Robin Despins**, **Chelsea Doerper**, **Amanda DuVal**, **Melissa Gambal**, **Angela Garcia**, **Daegan Haller**, **Nicholas Murphy**, **Gracie Peters**, **Joseph Rubino**, **John Slane**, **Matthew Wolfson**, **Kyle Fanelli** and **Bogdan Udrea**, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.;
Frederico Herrero, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

The dynamic behaviour of the atmosphere between 200-500 km is a function of several factors, such as solar radiation and weather events in the thermosphere. To determine an accurate atmospheric model of this region accurate measurements of total density as well as composition and temperature of the particles must be taken. Current average error deviation in satellite measurements of density and composition in LEO ranges from 10-15%, with the majority of error coming from uncertainty in the drag determination.1 To reduce the uncertainty, the Mini-Satellite for Drag Estimation (MinDE) design defines a drag coefficient that is independent of atmospheric temperature and composition. The drag coefficient is thus relatable to in-situ measurements of particle-surface momentum transfer data, which is predictable to within 1% accuracy. This reduced uncertainty, along with a highly accurate accelerometer and a suite of miniature mass spectrometers, provides a unique challenge in the design of the satellite. The paper presents the preliminary design for the drag satellite. [View Full Paper]

SESSION 21: ORBIT DETERMINATION II
Chair: Lisa Policastri, Applied Defense Solutions

AAS 12 – 260
Initial Orbit Determination via Gaussian Mixture Approximation of the Admissible Region

Kyle J. DeMars, National Research Council (NRC) Postdoctoral Research Fellow, 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.

The concept of the admissible region for a set of optical angles and their associated rates (with respect to time) provides a convenient method for bounding the set of all possible range/range-rate combinations that can provide Earth-bound orbit solutions (i.e. have negative orbital energy). Previous approaches to the problem of utilizing the admissible region for initial orbit determination have implemented discretization schemes to generate either hypotheses or triangulations which are then forecast in order to assimilate future incoming data. While both approaches have shown promise, neither approach provides a method by which probabilistic interpretations of the admissible region or the forward predictions may be made. This work investigates a method that employs a probabilistic approximation of the admissible region. In particular, Gaussian mixture approximations are applied to the admissible region in order to generate an initial probability density function (pdf) that is associated with uniform ambiguity within the admissible region. The Gaussian mixture pdf is then forecast using a Gaussian mixture filter and subsequent arcs of data are processed within the Gaussian mixture framework to refine the region of uncertainty. [View Full Paper]

AAS 12 – 261

Methods for Splitting Gaussian Distributions and Applications within the Aegis Filter

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

The tracking of space objects is characterized by the lack of frequent observations of the objects. As such, long periods of time in which the object's uncertainty must be propagated are often encountered. The AEGIS filter, which employs an online adaptation of a Gaussian mixtures representation of the uncertainty, has recently been proposed for uncertainty propagation, where the adaptation is based on application of splitting libraries. This work examines several cost functions based on information theoretic divergences and either enforcing or not enforcing moment-equality constraints to develop new splitting libraries and assesses the splitting libraries in the context of uncertainty propagation for space object tracking. It is shown via simulation studies that the Gamma divergence without enforcing moment-equality constraints produces the most accurate method for propagation of uncertainty. [View Full Paper]

AAS 12 – 262

Solution of the Liouville's Equation for Keplerian Motion: Application to Uncertainty Calculations

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

In the absence of process noise, the evolution of uncertainty from one time step to another is governed by a partial differential equation called the stochastic Liouville's equation. It differs from the Fokker-Planck Kolmogorov equation by the fact that there is no diffusion in the evolution process. Being a first order, linear, partial differential equation in n-dimensions, the Liouville's equation in several cases admits exact solutions. In general problems, the method of characteristics is employed to obtain solution density functions to this equation. It is shown in this paper that an application of the transformation of variables formula from probability theory yields an exact solution. It is also shown that this is identical to using the method of characteristics, appealing to the fact that the characteristic curves are automatically obtained by using the solution trajectories. For the special case of Keplerian motion, an analytic expression governing the probability density function evolution is derived. It is shown that by using the Kepler elements, the solution process is simplified significantly. [View Full Paper]

AAS 12 – 263

Non-Linear Propagation of Uncertainty with Non-Conservative Effects

K. Fujimoto and **D. J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, Colorado, U.S.A.

One topic of interest in space situational awareness (SSA) is the accurate and consistent representation of an observed object's uncertainty under non-linear dynamics, which can be approached analytically by employing a special solution to the Fokker-Planck dierential equations for Hamiltonian dynamical systems. In this paper, we expand this method to include the eects of non-conservative forces. In order to describe the evolution of a pdf over time for a dynamical system with no diusion, one only needs to find the solution flow to the dynamics regardless of whether the forces are conservative or not. [View Full Paper]

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Nonlinear Management of Uncertainties in Celestial Mechanics

Monica Valli, **Roberto Armellin**, **Pierluigi Di Lizia** and **Michèle R. Lavagna**, Department of Aerospace Engineering, Politecnico di Milano, Milan, Italy

The problem of nonlinear uncertainty propagation represents a crucial issue in celestial mechanics. In this paper a method for nonlinear propagation of uncertainties based on differential algebra is presented. Working in the differential algebra framework enables a general approach to nonlinear uncertainty propagation that can provide high estimate accuracy with low computational burden. The nonlinear mapping of the statistics is here shown adopting the two-body problem as working framework, including coordinate system transformations. The general feature of the proposed method is also demonstrated by presenting long-term integrations in a complex dynamical framework, such as the n-body problem or the HANDE model. [View Full Paper]

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Quadrature Methods for Orbit Uncertainty Propagation under Solar Radiation Pressure

Matthew R. Turnowicz, **Bin Jia**, **Ming Xin** and **Yang Cheng**, Department of Aerospace Engineering, Mississippi State University, Mississippi State, Mississippi, U.S.A.; **Kyle J. DeMars**, National Research Council (NRC) Postdoctoral Research Fellow, 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.

Long-term orbit uncertainty propagation for space objects needs to account for both conservative and non-conservative effect such as the effect of solar radiation pressure. With the flat-plate model for solar radiation pressure, the orbital motion is coupled with the attitude motion, resulting in high-dimensional integration in propagation of the moments, e.g., mean and covariance, of the orbital and attitude parameters. Three quadrature methods—the Monte Carlo method, the quasi-Monte Carlo method, and the sparse grid method—are applied to the moment propagation problem and compared in simulation of a space object in geosynchronous orbit over one day, one week, and one month. The quadrature methods are straightforward to implement and can accommodate Gaussian and non-Gaussian parametric distributions. [View Full Paper]

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(Paper Withdrawn)

SESSION 22: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL II
Chair: Dr. Felix Hoots, The Aerospace Corporation

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Application of the Generalized Transfer Equation to Mission Planning

Darren D. Garber, Department of Astronautical Engineering, University of Southern California, Los Angeles, California, U.S.A.; **Firdaus Udwadia**, Department of Aerospace and Mechanical Engineering, Civil Engineering and Mathematics, University of Southern California, Los Angeles, California, U.S.A.

This paper describes the Generalized Transfer Equation which extends the technique of patched conics to now include any curve as a template to account for perturbed orbits and powered flight trajectories. Through the derived Generalized Transfer Equation the velocity necessary to transfer between any two orbits can be determined directly. The utility of this approach is demonstrated for maneuver and mission planning by enabling the use of both impulsive maneuvers and low-thrust profiles to model the trajectory. [View Full Paper]

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(Paper Withdrawn)

AAS 12 – 269
Frozen Orbits for Scientific Missions Using Rotating Tethers

Hodei Urrutxua, **Jesús Peláez** and **Martin Lara**, Space Dynamics Group, Technical University of Madrid (UPM), Spain

We derive a semi-analytic formulation that permits to study the long-term dynamics of fast-rotating inert tethers around planetary satellites. Since space tethers are extensive bodies they generate non-keplerian gravitational forces which depend solely on their mass geometry and attitude, that can be exploited for controlling science orbits. We conclude that rotating tethers modify the geometry of frozen orbits, allowing for lower eccentricity frozen orbits for a wide range of orbital inclination, where the length of the tether becomes a new parameter that the mission analyst may use to shape frozen orbits to tighter operational constraints. [View Full Paper]

AAS 12 – 270
Backstepping Adaptive Control for Flexible Space Structure with Non-Collocated Sensors and Actuators

Min Liu, **Hong Guan**, **Shijie Xu** and **Chao Han**, School of Astronautics, Beihang University, Beijing, China

The control of noncollocated flexible space structure is a challenging control problem. Although Simple Adaptive Control (SAC) is widely studied both in theory and application in flexible structure control, it is restricted by the Almost Strict Positive Real (ASPR) conditions. And in most practical control problems, the ASPR conditions are not satisfied, for their relative degree is more than one. Therefore, based on the SAC theory, this paper proposes a backstepping adaptive control algorithm which suits the system with arbitrary relative degree. This method inheriting the characteristics of SAC, can be adaptive online for the parameters uncertainties. Then, the application of the proposed controller in large flexible space structure is studied. Since the kinematics subsystem of flexible space structure is accurate known, a constant coefficient feedback intermediate controller is designed to stabilize the kinematics. Besides, an adaptive controller is designed for the dynamics subsystem with parameter uncertainties by adopting backstepping control method. The simulation results both in the collocated case and noncollocated case validate the proposed controller. [View Full Paper]

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(Paper Withdrawn)

AAS 12 – 272

Solving and Analyzing Relative Lambert's Problem through Differential Orbital Elements

Chang-xuan Wen, **Yu-shan Zhao**, **Bao-jun Li** and **Peng Shi**, School of Astronautics, Beijing University of Aeronautics and Astronautics, Haidian District, Beijing, China

A novel approach based on Lagrange's time equation and differential orbital elements is developed to solve the relative Lambert's problem on circular reference orbit. In comparison with the conventional Clohessy-Wiltshire equation, the proposed method can directly obtain the change of orbital elements. This advantage enables us to account for the singularities occurred in relative Lambert's problem. Results reveal that relative velocities depend on five differential orbital elements between the transfer orbit and the reference orbit. Accordingly, singularities can be attributed to any significant change of the semi-major axis, eccentricity or orbital plane. Furthermore, adjusting the initial and final relative positions properly can remove some of the singularities. A numerical simulation based on classic Lambert's formula for a rendezvous mission in closed range demonstrates all the analytical results. [View Full Paper]

AAS 12 – 273

Three Lambert Formulations with Finite, Computable Bounds

Marc DiPrinzio, Mission Analysis and Operations Department, The Aerospace Corporation, Chantilly, Virginia, U.S.A.

Three parameterizations of the classical Lambert problem are described. The necessary relations are derived such that the flight path angle, the true anomaly, and the argument of perigee can each be used as the independent variable to solve Lambert's problem. It is shown that each of these parameters have finite, computable bounds; as a result, the desired root is "bracketed" in this known interval. While many root-finding algorithms exist, some of these offer guaranteed convergence (at least theoretically) for a bracketed root. Techniques are also described that extend these formulations to multiple revolution transfers. While these methods are unlikely to replace the elegant transformational methods of Battin or Gooding, the algorithms remain of interest due to their novelty and simplicity. [View Full Paper]

AAS 12 – 274

Review of Quadrilateralized Spherical Cube and Views of Future Work on Spacecraft Collisions (Abstract and Biography Only)

F. Kenneth Chan

The first topic concerns an efficient Earth database structure for rapidly storing and retrieving highresolution remotely-sensed global data. This formulation is based on the concept of a "Quadrilateralized Spherical Cube" (QLSC). It was implemented for global usage by the Navy in 1977, and since then it has been adopted by other government agencies such as NASA in various applications, the first being the Cosmic Background Explorer (COBE). For the past three decades QLSC, or some derivative of it, has been used by astronomers and astrophysicists for star-mapping and radiation-cataloging to the celestial sphere. Atmospheric and ocean scientists use it for database structure because of its exceptional efficiency in data archiving and retrieval. The QLSC and its associated Quadtree are presently used by computer scientists in many geographical information systems for data processing. It is also used in map projections because there are no singularities at the poles or elsewhere, as is the case with other equal-area mapping schemes.

The second topic concerns the modeling and computation of spacecraft collision probability for the case in which the statistics no longer obey Gaussian distributions, or the case where the space debris is so sparse as not to be amenable to description using Poisson statistics. An outline is given for the computation of collision probability of close encounters when the probability density functions are non-Gaussian. A discussion is included on the estimation of debris density when there are pronounced inhomogenieties in the spatial distribution of the debris. [View Full Summary]

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