ASTRODYNAMICS 2013

Edited by
Stephen B. Broschart
James D. Turner
Kathleen C. Howell
Felix R. Hoots

American Astronautical Society

Volume 150

ADVANCES IN THE ASTRONAUTICAL SCIENCES

ASTRODYNAMICS 2013

EDITORS
Dr. Stephen B. Broschart — Jet Propulsion Laboratory
Dr. James D. Turner — Texas A&M University
Prof. Kathleen C. Howell — Purdue University
Dr. Felix R. Hoots — The Aerospace Corporation

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Front Cover Illustration:

Exciting recent successes and proposed concepts in astrodynamics.

Background: Herschel's view of the Horsehead Nebula. Credit: ESA/Herschel/PACS, SPIRE/N. Schneider, Ph. André, V. Könyves (CEA Saclay, France) for the "Gould Belt survey" Key Programme.
Upper Left: SpaceX Dragon being captured by the Canadian "Canadarm 2" robotic arm as part of International Space Station Expedition 34 on March 3, 2013. Credit: NASA.
Upper Right: Asteroid Toutatis as seen by the Chinese Chang'e 2 during a close flyby on December 13, 2012. Credit: Chinese Academy of Sciences / Daniel Macháček (for creating the composite image)
Bottom Left: Artist's conception of the proposed Asteroid Redirect Mission approaching a small asteroid. Credit: NASA/Advanced Concepts Lab.
Bottom Right: Mars Science Laboratory "self-portrait," taken using the rover's MAHLI instrument on February 3 and May 10, 2013. Credit: NASA/JPL-Caltech/MSSS.
Cover Design: Steve Broschart and Ted Sweetser, Jet Propulsion Laboratory.

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CONTENTS

Complete reference information can be found in the table of contents, the numerical index and the author index from the bound version of the proceedings. Look there for other publication information.

FOREWORD

The 2013 Astrodynamics Conference was hosted by the American Astronautical Society (AAS) and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA). The conference was held August 11–15, 2013, Hilton Head, South Carolina, U.S.A. There were some 205 papers presented in 28 technical sessions. Session topics included Space Situational Awareness (SSA): Detection and Estimation; Mission Operations; Nonlinear Modeling and Analysis Methods; Spacecraft Autonomy and Rendezvous; Solar Sails, Tethers, and Large Space Structures; Earth Orbiters; Maneuver Design; Attitude Determination and Dynamics; Space Situational Awareness (SSA): Prediction and Uncertainty; Orbit Determination and Estimation; Dynamical Systems Theory; Formation Flying and Relative Motion; Interplanetary Mission Design and Concepts; Close-proximity Operations near Primitive Bodies; Attitude Guidance and Control; Space Situational Awareness (SSA): Orbit Debris Modeling and Mitigation; Spacecraft Guidance, Navigation, and Control; Orbit Dynamics; Atmospheric Flight and Entry, Descent, and Landing; Lunar Mission Design and Concepts; Special Session: High-performance and On-board Computing Architectures; Space Situational Awareness (SSA): Collisions and Conjunctions; Low-thrust Trajectory Design; and Primitive Body Mission Design and Concepts.

These astrodynamics conferences have been held annually since the mid-1960s, managed alternately by the American Astronautical Society and the American Institute of Aeronautics and Astronautics. Every second year the American Astronautical Society publishes the proceedings. The proceedings usually consist of a hard-copy volume or set of volumes plus a CD ROM (microfiche supplements in earlier years). This volume, *Astrodynamics 2013*, Volume 150, *Advances in the Astronautical Sciences*, consists of three parts totaling about 3,600 pages, plus a CD ROM which includes the papers in digital form. All of the available papers appear in full in Volume 150. A chronological index and an author index are appended to the third part of the volume. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume.

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

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

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

The current proceedings are valuable 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 ASTRODYNAMICS VOLUMES

Astrodynamics 2013 appears as Volume 150, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Conference 2013.

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

Astrodynamics 2009, Volume 135, Advances in the Astronautical Sciences, Eds. A.V. Rao et al., 2446p, three parts plus a CD ROM Supplement.

Astrodynamics 2007, Volume 129, *Advances in the Astronautical Sciences*, Eds. R.J. Proulx et al., 2892p, three parts plus a CD ROM Supplement.

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

Astrodynamics 2003, Volume 116, *Advances in the Astronautical Sciences*, Eds. J. de Lafontaine et al., 2746p, three parts plus a CD ROM Supplement.

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

Astrodynamics 1999, Volume 103, *Advances in the Astronautical Sciences*, Eds. K.C. Howell et al., 2724p, three parts.

Astrodynamics 1997, Volume 97, *Advances in the Astronautical Sciences*, Eds. F.R. Hoots et al., 2190p, two parts.

Astrodynamics 1995, Volume 90, *Advances in the Astronautical Sciences*, Eds. K.T. Alfriend et al., 2270p, two parts; Microfiche Suppl., 6 papers (Vol. 72 *AAS Microfiche Series*).

Astrodynamics 1993, Volume 85, *Advances in the Astronautical Sciences*, Eds. A.K. Misra et al., 2750p, three parts; Microfiche Suppl., 9 papers (Vol. 70 *AAS Microfiche Series*)

Astrodynamics 1991, Volume 76, *Advances in the Astronautical Sciences*, Eds. B. Kaufman et al., 2590p, three parts; Microfiche Suppl., 29 papers (Vol. 63 *AAS Microfiche Series*)

Astrodynamics 1989, Volume 71, *Advances in the Astronautical Sciences*, Eds. C.L. Thornton et al., 1462p, two parts; Microfiche Suppl., 25 papers (Vol. 59 *AAS Microfiche Series*)

Astrodynamics 1987, Volume 65, *Advances in the Astronautical Sciences*, Eds. J.K. Soldner et al., 1774p, two parts; Microfiche Suppl., 48 papers (Vol. 55 *AAS Microfiche Series*)

Astrodynamics 1985, Volume 58, *Advances in the Astronautical Sciences*, Eds. B. Kaufman et al., 1556p, two parts; Microfiche Suppl. 55 papers (Vol. 51 *AAS Microfiche Series*)

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

Astrodynamics 1981, Volume 46, *Advances in the Astronautical Sciences*, Eds. A.L. Friedlander et al., 1124p, two parts; Microfiche Suppl., 41 papers (Vol. 37 *AAS Microfiche Series*)

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

Astrodynamics 1977, Volume 27, *AAS Microfiche Series*, 73 papers

Astrodynamics 1975, Volume 33, *Advances in the Astronautical Sciences*, Eds., W.F. Powers et al., 390p; Microfiche Suppl., 59 papers (Vol. 26 *AAS Microfiche Series*)

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

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

Spaceflight Mechanics 2013, Volume 148, *Advances in the Astronautical Sciences*, Eds. S. Tanygin et al., 4176p., four parts, plus a CD ROM supplement.

Spaceflight Mechanics 2012, Volume 143, *Advances in the Astronautical Sciences*, Eds. J.V. McAdams et al., 2612p., three parts, plus a CD ROM supplement.

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

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

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

Spaceflight Mechanics 2008, Volume 130, *Advances in the Astronautical Sciences*, Eds. J.H. Seago et al., 2190p., two parts, plus a CD ROM supplement.

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

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

Spaceflight Mechanics 2005, Volume 120, *Advances in the Astronautical Sciences*, Eds. D.A. Vallado et al., 2152p., two parts, plus a CD ROM supplement.

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

Spaceflight Mechanics 2003, Volume 114, *Advances in the Astronautical Sciences*, Eds. D.J. Scheeres et al., 2294p, three parts, plus a CD ROM supplement.

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

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

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

Spaceflight Mechanics 1999, Volume 102, *Advances in the Astronautical Sciences*, Eds. R.H. Bishop et al., 1600p, two parts.

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

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

Spaceflight Mechanics 1996, Volume 93, *Advances in the Astronautical Sciences*, Eds. G.E. Powell et al., 1776p, two parts; Microfiche Suppl., 3 papers (Vol. 73 *AAS Microfiche Series*).

Spaceflight Mechanics 1995, Volume 89, *Advances in the Astronautical Sciences*, Eds. R.J. Proulx et al., 1774p, two parts; Microfiche Suppl., 5 papers (Vol. 71 *AAS Microfiche Series*).

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

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

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

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

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Robert H. Jacobs, Series Editor

PREFACE

The 2013 Astrodynamics Specialist Conference was held at the Hilton Head Marriott Resort, Hilton Head, South Carolina, August 11-15, 2013. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Technical Committee (TC) and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics TC. The 217 people who registered for the meeting included 89 students as well as professional engineers, scientists, and mathematicians representing the government, industry, and academic sectors of the United States and 14 other countries. There were 205 papers presented in 28 sessions on topics spanning the breadth of current research in astrodynamics and space-flight mechanics.

Our plenary session this year was given by David Barnhart of the Defense Advanced Research Projects Agency (DARPA). His talk, entitled “Mambo Dogfish to the Banana Patch,” addressed the challenge of fruitfully aligning technological advances with government policy to unleash their true potential. We also hosted a well-attended and interactive special interest session on NASA’s recent Asteroid Redirection Mission (ARM) mission concept, led by Nathan Strange of the Jet Propulsion Laboratory (JPL).

The editors extend their gratitude to each of the Session Chairs that helped make this meeting a success: Maruthi Akella, Rodney Anderson, Brent Barbee, Angela Bowes, Al Cangahuala, W. Todd Cerven, Carolin Frueh, Roberto Furfaro, Yanping Guo, Marcus Holzinger, John Junkins, Don Mackison, Craig McLaughlin, Jay McMahon, Robert Melton, Jeff Parker, Glenn Peterson, Ryan Russell, Hanspeter Schaub, Puneet Singla, Tom Starchville, Ted Sweetser, James Turner, Benjamin Villac, Roby Wilson, Ahmad Bani Younes, Renato Zanetti, and Zhiqiang (Joe) Zhou. Our gratitude also goes to all the people who helped us pull together the conference advertising, programs, and proceedings, including: Mike Gabor, Robert Jacobs, Jim Kirkpatrick, Terry McDonald, Ryan Park, Hanspeter Schaub, John Seago, Holly Stewart, Sergei Tanygin, Diane Thompson, and Christine Williams. Finally, we graciously thank the Aerospace Corporation for sponsoring the printing of the conference programs.

Dr. Stephen B. Broschart
Jet Propulsion Laboratory
AAS Technical Chair

Prof. Kathleen C. Howell
Purdue University
AAS General Chair

Dr. James D. Turner
Texas A&M University
AIAA Technical Chair

Dr. Felix R. Hoots
The Aerospace Corporation
AIAA General Chair

PAPERS BY NUMBER AND TITLE

Volume 150 I, II & III

ADVANCES IN THE ASTRONAUTICAL SCIENCES
ASTRODYNAMICS 2013 (2014)

(AAS/AIAA Astrodynamics Specialist Conference, August 11–15, 2013, Hilton Head, South Carolina, U.S.A.)

SESSION 1: SSA I: DETECTION AND ESTIMATION

SESSION 2: MISSION OPERATIONS

SESSION 3: NONLINEAR MODELING AND ANALYSIS METHODS

SESSION 4: SPACECRAFT AUTONOMY AND RENDEZVOUS

SESSION 5: SOLAR SAILS, TETHERS AND LARGE SPACE STRUCTURES I

SESSION 6: EARTH ORBITERS

SESSION 10: ORBIT DETERMINATION AND ESTIMATION I

SESSION 11: DYNAMICAL SYSTEMS THEORY

SESSION 14: CLOSE-PROXIMITY OPERATIONS NEAR PRIMITIVE BODIES

SESSION 15: ORBIT DETERMINATION AND ESTIMATION II

SESSION 16: ATTITUDE GUIDANCE AND CONTROL

SESSION 17: SSA III: ORBIT DEBRIS MODELING AND MITIGATION

AAS 13 – 848 Effects of the Rotational Motion of Debris Objects on the Prediction of Their Orbital Motions, John E. Cochran, Jr. and Thomas B. Walsh

AAS 13 – 849 A Mathematical Formulation to Describe Density of Particles in an Inhhomogeneous Distribution, Ken Chan

AAS 13 – 850 Orbit Determination of ETS-8 by Pegasus Observatory in Kyushu University, Hideaki Hinagawa and Toshiya Hanada

AAS 13 – 851 Space-Based Characterization of Debris in Low-Earth Orbit Via LWIR Imaging, Paul D. McCall, Madeleine L. Naudeau, Jean H. Andrian, Armando Barreto, Naphtali Rishe and Malek Adjouadi

SESSION 18: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL

AAS 13 – 852 Heuristic Suboptimal Solutions to Reduce Velocity Pointing Errors for Spinning, Thrusting Spacecraft, Kaela M. Martin and James M. Longuski

AAS 13 – 853 Image Processing of Illuminated Ellipsoid, Daniele Mortari, Francesco de Dilectis and Christopher D'Souza

AAS 13 – 855 Thrusters Time-Delayed Control Allocation for Soft-Landing of Lunar Lander, Jae-Wook Kwon, Bong Un Lee, Hyochoong Bang and Gwanghyeok Ju

AAS 13 – 856 Operations Concept, Hardware Implementation and Ground-Test Verification of a Hazard Detection System for Autonomous and Safe Precision Lunar Landing, John M. Carson, Erik S. Bailey, Nikolas Trawny, Andrew E. Johnson, Vincent E. Roback, Farzin Amzajerdian and Robert A. Werner

AAS 13 – 857 On Six D.O.F Relative Orbital Motion Parametrization Using Rigid Bases of Dual Vectors, Daniel Condurache and Adrian Burlacu

AAS 13 – 858 Adaptive Position and Attitude Tracking Controller for Satellite Proximity Operations Using Dual Quaternions, Nuno Filipe and Panagiotis Tsiotras

AAS 13 – 859 A Least Squares Solution for Estimation of a Planar Homography, Manoranjan Majji, Martin Diz and David Truong

AAS 13 – 860 Halo Orbit Targeting Guidance Via Higher Order Sliding Techniques, Jules Simo, Roberto Furfaro and Daniel R. Wibben

AAS 13 – 861 Distributed Internet-Enabled Simulation/Testbed Architecture, Marcelo Gonzalez-Oberdoerffer, Darren Zanon and Ravishankar Mathur

SESSION 19: ORBIT DYNAMICS

AAS 13 – 862 The Two Body Problem Elevated to the Complex Domain, Donald L. Hitzl and Frank Zele

AAS 13 – 863 Trajectory Dynamics of Gas Molecules and Galaxy Formation, James K. Miller, Pedro J. Llanos and Gerald R. Hintz

AAS 13 – 864 Searching for Orbits That Can be Controlled by Natural Forces, Thais C. Oliveira, Antonio F. B. A. Prado, Evandro M. Rocco and Arun K. Misra

AAS 13 – 865 Long-Term Dynamics and Stability of GEO Orbits: The Primacy of the Laplace Plane, Aaron J. Rosengren, Daniel J. Scheeres and Jay W. McMahon

SESSION 20: ATMOSPHERIC FLIGHT AND ENTRY, DESCENT AND LANDING

SESSION 21: LUNAR MISSION DESIGN AND CONCEPTS

SESSION 22: ATTITUDE DETERMINATION AND DYNAMICS II

SESSION 23: SOLAR SAILS, TETHERS, AND LARGE SPACE STRUCTURES II

SESSION 24: SPECIAL SESSION:
HIGH-PERFORMANCE AND ON-BOARD COMPUTING ARCHITECTURES

SESSION 25: SSA IV: COLLISIONS AND CONJUNCTIONS

AAS 13 – 906	Space Traffic Management (STM), Duane E. Bird
AAS 13 – 907	BLITS: A Forensic Analysis of a Probable Collision, Roger Thompson, Glenn E. Peterson, John P. McVey, Robert E. Markin and Marlon E. Sorge
AAS 13 – 908	Non-Gaussian Collision Probability, Ken Chan
AAS 13 – 910	Collision Risk Assessment and Avoidance Maneuvers – First Experience With ESA's New Tool CORAM, K. Merz, I. Grande-Olalla, N. Sanchez-Ortiz and J. A. Pulido
AAS 13 – 911	A Non-Combinatorial Approach for Efficient Conjunction Analysis, Michael Mercurio, Puneet Singla and Abani Patra
AAS 13 – 912	Recommended Risk Assessment Techniques and Thresholds for Launch COLA Operations, M. D. Hejduk, D. Plakalovic, L. K. Newman, J .C. Ollivierre, M. E. Hametz, B. A. Beaver and R. C. Thompson
AAS 13 – 913	Analytical Non-Linear Conjunction Assessment Via State Transition Tensors in Orbital Element Space, Kohei Fujimoto and Daniel J. Scheeres

SESSION 26: FORMATION FLYING AND RELATIVE MOTION II

AAS 13 – 915	Development of Integrated Orbit and Attitude Hardware-In-The-Loop Simulator System for Satellite Formation Flying, Han-Earl Park, Sang-Young Park, Sung-Woo Kim and Chandeok Park
AAS 13 – 917	New Research Methodology for Earth Periodic Coverage and Regularities in Parametric Localization of Optimal Low-Earth-Orbit Satellite Constellations, Yury N. Razoumny
AAS 13 – 918	Coordinated Control of Autonomous Vehicles in Three-Dimensional Rotating Formations, D. Thakur and M. R. Akella
AAS 13 – 919	Sliding Mode Control for Decentralized Spacecraft Formation Flying Using Geometric Mechanics, Daero Lee, Eric A. Butcher and Amit K. Sanyal
AAS 13 – 920	Optimal Collision Avoidance Maneuver for Fractionated Spacecraft Within Networked System, Ran Dai
AAS 13 – 921	O3B Constellation Orbit Raising and Maintenance, Sébastien Herbinière, Joël Amalric, Alexandre Kaltenbach and Olivier Vadam
AAS 13 – 923	Constrained Discrete-Time State-Dependent Riccati Equation Control for Decentralized Multi-Agent Systems, Insu Chang, Joseph Bentsman, Sang-Young Park and Chandeok Park

SESSION 27: LOW-THRUST TRAJECTORY DESIGN

AAS 13 – 924	Robust Global Optimization of Low-Thrust, Multiple-Flyby Trajectories, Donald H. Ellison, Jacob A. Englander and Bruce A. Conway
AAS 13 – 925	Optimization of Preliminary Low-Thrust Trajectories From GEO-Energy Orbits to Earth-Moon, L1, Lagrange Point Orbits Using Particle Swarm Optimization, Andrew J. Abraham, David B. Spencer and Terry J. Hart
AAS 13 – 926	Minimum-Time Low-Earth Orbit to High-Earth Orbit Low-Thrust Trajectory Optimization, Kathryn F. Schubert and Anil V. Rao

SESSION 1: SSA I: DETECTION AND ESTIMATION
Chair: Moriba Jah, Air Force Research Laboratory

AAS 13 – 700
(Paper Withdrawn)

AAS 13 – 701
Detection Probability of Earth Orbiting Objects Using Optical Sensors

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

The space around Earth is becoming more congested with increasing launches and the proliferation of debris. Over 93 percent of the catalogued objects are uncontrolled and non-operational space objects, so-called space debris. The origin, material, and attitude motion of the majority of those objects are unknown, even if orbital information is available. In the realm of space situation awareness (SSA), information on state, attitude and material of all objects is sought.

For Earth orbiting objects, especially those in high altitude orbits as in the geostationary ring, ground based optical sensors are a cost-efficient way to gain information. Resolved images, however, can only be gained of satellites and space debris objects in Low Earth orbits with ground based optical sensor capabilities, because atmospheric seeing may limit the (theoretically attainable) resolution of the sensor. Position information, that is astrometric line-of-sight position and tangent velocity information and brightness (magnitude) information may be extracted from series of subsequent images.

The reflected light received by the telescope depends on the observation geometry, object size, object reflection properties and the attitude motion of the object. The object needs to be in the field of view (FOV) to be detected as a minimal criteria. However, the crucial factor is the signal to noise ratio (SNR) of the point source on the telescope frames. The SNR does not only affect the probability of detection, but also the measured position accuracy and magnitude errors. Objects with a rapid attitude motion and non-spherical shape and/or non-uniform reflection properties result in unresolved object images, which appear with rapidly changing brightness on the detector frame.

In this paper, the detection probability's dependence on object state, its characteristics and orbital region (distance to the observer and observation scenario) that are investigated. The effect of sensor specifications (aperture size, quantum efficiency etc.) and geometry on detection probability and brightness errors using different observation scenarios are shown. [View Full Paper]

AAS 13 – 702

An Optimal Control-Based Estimator for Maneuver Detection and Reconstruction

Daniel P. Lubey and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

A new type of estimator that incorporates optimal control and outputs a control policy is developed and analyzed in this study. The estimator is developed in a similar manner to a Kalman Algorithm with an almost identical form, but with additional properties for more accurate tracking. Unlike the Kalman Algorithm, this estimator frees up the initial state, which results in an algorithm that decouples a priori state uncertainty and dynamics uncertainty. The dynamic uncertainty inflates the state covariance in an automatic fashion that prevents filter saturation. The algorithm also outputs control estimates that may be used to both identify the presence of mismodeled dynamics and quantify those mismodeled dynamics. Simulations demonstrate the performance of this estimator compared to the Kalman Algorithm in several systems with varying types of dynamic mismodeling. [View Full Paper]

AAS 13 – 703
(Paper Withdrawn)

AAS 13 – 704

Probabilistic Initial Orbit Determination Using Radar Returns

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

The most complete description of the state of a system at any time is given by knowledge of the probability density function, which describes the locus of possible states conditioned on any available measurement information. When employing radar returns, an admissible region approach provides a physics-based region of the right-ascension rate/declination rate space of possible Earth-bound orbit solutions. This work develops a method that employs a probabilistic interpretation of the admissible region and approximates the admissible region by a Gaussian mixture to formulate an initial orbit determination solution. [View Full Paper]

AAS 13 – 705

Multiple Hypothesis Tracking (MHT) for Space Surveillance: Theoretical Framework

Jeffrey M. Aristoff, **Joshua T. Horwood**, **Navraj Singh** and **Aubrey B. Poore**, Numerica Corporation, Loveland, Colorado, U.S.A.;
Carolyn Sheaff, Air Force Research Laboratory AFRL/RIED, Rome, New York, U.S.A.; **Moriba K. Jah**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

The need to accurately track breakups, satellite clusters, and other closely-spaced objects requires new, robust, and autonomous methods for space surveillance to enable the development and maintenance of the space catalog and to support the overall SSA mission. This paper presents a newly-developed, statistically-robust, system-level, multiple hypothesis tracking (MHT) capability for joint catalog maintenance, uncorrelated track (UCT) resolution, and initial orbit determination. Emphasis is placed on describing some of the unique components contained within the authors' implementation of MHT, including the multi-frame data association problem and the statistical framework used for scoring the likelihood that a sequence of measurements, UCTs, and other reports emanate from a common object. As demonstrated in a companion paper, the MHT system provides excellent realtime tracking performance in realistic large-scale multi-sensor tracking scenarios consisting of closely- and widely-spaced objects over multiple regimes of space. [View Full Paper]

AAS 13 – 706

Guaranteed Approach for Orbit Determination With Limited Measurements

Zakhary N. Khutorovsky, Interstate Joint-Stock Corp. "Vympel." Moscow, Russia; **Alexnder S. Samotokhin**, M.V. Keldysh Institute of Applied Mathematics of Russian Academy of Sciences, Moscow, Russia; **Kyle T. Alfriend**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

A non-statistical statement of the orbit determination of a near-Earth space object in Earth orbit with certain limitations on the measurement errors is considered. The optimization criterion and the algorithms satisfying the limited error criterion are given. As distinguished from the traditionally used least squares method, the interpolated algorithms are adapted to the measurement errors and always provide a guaranteed error range of the estimated parameters. The central algorithms, optimal in measurement errors in the minimax statement, have robust properties with regards to such errors. The projective robust-interpolated algorithms are independent of the measurement error upper limit. Computational schemes are given for the most practically interesting central and projective algorithms. The accuracy characteristics of such algorithms are given for different distributions of measurement errors using a mathematical simulation for typical situations occurring in the maintenance of a space object catalog. It is demonstrated that the errors in the orbit determination of a space object using this nonstatistical approach may be less than the least-squares method errors. [View Full Paper]

AAS 13 – 707

Optical Sensor Constraints on Space Object Detection and Admissible Regions

Johnny L. Worthy III and **Marcus J. Holzinger**, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.; **Kohei Fujimoto**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

This paper presents work on a model to simulate the space debris environment based on optical sensor detection constraints of line of sight, illumination, and visual magnitude. Through analysis, the performance of pointing trajectories, such as the automated sensors in the Space Surveillance Network (SSN), can be optimized based on the shapes of these constraints. This application is particularly of interest to space based sensors and the design of space based space surveillance missions. The presented constraints are also found to be dependent on range to the space object. This dependence is used to apply additional constraints to the admissible region further aiding in initial state estimation of space objects observed from space. [View Full Paper]

AAS 13 – 708

Towards an Artificial Space Object Taxonomy

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Object recognition is the first step in positively identifying a resident space object (RSO), i.e. assigning an RSO to a category such as GPS satellite or space debris. *Object identification* is the process of deciding that two RSOs are in fact one and the same. Provided we have appropriately defined a satellite taxonomy that allows us to place a given RSO into a particular class of object without any ambiguity, one can assess the probability of assignment to a particular class by determining how well the object satisfies the unique criteria of belonging to that class. Ultimately, tree-based taxonomies delineate unique signatures by defining the minimum amount of information required to positively identify a RSO. Therefore, taxonomic trees can be used to depict hypotheses in a Bayesian object recognition and identification process. This work describes a new RSO taxonomy along with specific reasoning behind the choice of groupings. We will demonstrate how to implement this taxonomy in Figaro, an open source probabilistic programming language. [View Full Paper]

AAS 13 – 709
(Paper Withdrawn)

SESSION 2: MISSION OPERATIONS
Chair: Zhiqiang Zhou, NASA Langley Research Center

AAS 13 – 710
(Paper Withdrawn)

AAS 13 – 711

Navigation of the GRAIL Spacecraft Pair Through the Extended Mission at the Moon

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The GRAIL extended mission (XM) dramatically expands the scope of GRAIL's gravity science investigation by flying the pair of spacecraft at the lowest orbit the flight team can safely support. From the perspective of the Navigation team, the low orbit altitude introduces new challenges. At this lower altitude, navigation is more sensitive to higher-order terms of the gravity field so that orbit determination solutions are more difficult and there is less certainty of achieving maneuver targets. This paper reports on the strategy and performance of the Navigation system for GRAIL's XM. On a weekly basis, the Navigation team provided reference trajectory updates, designed three maneuvers, and reconstructed the execution of those maneuvers. In all, the XM involved 55 planned maneuvers; five were canceled. The results of the Navigation team's efforts, in terms of maintaining the reference-trajectory targets, satisfying requirements, and achieving desired separation distances, are assessed. [View Full Paper]

AAS 13 – 712

GRAIL TCM-5 Go/No-Go: Developing Lunar Orbit Insertion Criteria

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The Gravity Recovery and Interior Laboratory (GRAIL) mission successfully completed mapping the Moon's gravity field to an unprecedented level. The mission success was critically dependent on the success of the Lunar Orbit Insertion (LOI). It was somewhat unfamiliar as it involved an elliptical approach from a low-energy trans-lunar cruise trajectory via Sun-Earth three-body region rather than a more conventional hyperbolic approach from a direct Earth-to-Moon transfer. In addition, how its delivery dispersion affected the science formation of the two spacecraft was not well understood. In this paper we establish a set of LOI criteria to meet all the requirements and we use these criteria to establish Go/No-Go boundaries of the last, statistical Trajectory Correction Maneuvers (TCM-5s) for operations. In the end both spacecraft were found to be within the established boundaries and TCM-5s of both spacecraft were cancelled.
[View Full Paper]

AAS 13 – 713

Conjunction Assessment Concept of Operations for the Magnetospheric Multiscale (MMS) Mission

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While collisions between the four MMS spacecraft are unlikely, the consequence of a collision between two spacecraft is mission failure. The MMS mission design requirements state that no more than 1 in 1000 unsafe close approaches may remain undetected. However, mission operators and the science team require that collision risk mitigation maneuvers are not excessively frequent and hence that no more than 1 in 20 collision alarms may occur when the conjunction is safe. These competing requirements—collision avoidance conservatism vs. unnecessary interruption of science activities and inconvenience to the ground system—induce the conjunction assessment Operations Concept for the MMS mission. [View Full Paper]

AAS 13 – 714
(Paper Withdrawn)

AAS 13 – 715

Telemetry Parameter Period-Based Anomaly Detection

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It is popular for a satellite control center to use Limit-Check algorithm to analyses telemetry parameters down from on-orbit satellites to detect any anomaly. Limit-check algorithm is simple and effective to deal with static telemetry parameter but can't find an anomaly whose telemetry parameter's value is still within the given limit. This paper presents a novel method which takes advantage of the dynamic and periodic characteristic of telemetry parameters to solve this problem. Using periodogram spectral estimation to get the cycle of a telemetry parameter from an on-board unit, we find a regularity that a parameter's value of each cycle is almost same or very close when the unit is in good condition. If the regularity is broken it means something wrong. Therefore, we establish an auto-regressive moving average (ARMA) model for the data sampled periodically from a raw telemetry parameter. We use the model to predicate what the next parameter's value should be and use it to compare with the actual measured value to find any anomaly. To verify the method's validation, we use it to analyze the telemetry parameters downloaded from an China on-orbit XX-1 satellite in 2012 and immediately find an anomaly happened in its solar panel rotational unit. Any anomaly like this whose telemetry parameter's value is within the given limit can't be detected before only by Limit-check algorithm. The novel method is more sensitive to find any subtle anomaly and can be used as a complement to Limit-check algorithm to guarantee on-orbit satellite's health. [View Full Paper]

AAS 13 – 716

Multipoint Extension of Pontryagin's Maximum Principle Applied to the Optimal Attitude Scheduling of an Imaging Satellite

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A new result in nonlinear optimal control is applied to the scheduling of high-resolution imaging of successive ground targets from an orbiting satellite. The new result is a rigorous statement and proof of Pontryagin's Maximum Principle extended to the multipoint case. The paper focuses on explaining the new result, outlines its proof with intuition in mind, demonstrates its wide applicability, and solves the attitude scheduling problem for a low-budget satellite application. [View Full Paper]

AAS 13 – 717

Cassini Solstice Mission Maneuver Experience: Year Three

Sean V. Wagner, **Juan Arrieta**, **Yungsun Hahn**, **Paul W. Stumpf**, **Powtawche N. Valerino** and **Mau C. Wong**, Flight Path Control Group and the Cassini Navigation Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Solstice Mission is the final extension of the Cassini spacecraft's tour of Saturn and its moons. To accommodate an end of mission in 2017, the maneuver decision process continues to be refined. This process includes determining whether a maneuver is performed or cancelled, choosing the engine to use for execution, and deciding the maneuver design strategy. Additionally, the Cassini Project now prioritizes saving propellant over minimizing maneuver cycles. This paper highlights 30 maneuvers planned from June 2012 through July 2013, targeted to nine Titan flybys and the final Rhea encounter in the mission. To maintain the prescribed trajectory or to preserve downstream ΔV, 27 of the 30 maneuvers were performed. Through execution-error modeling and analysis, the majority of the observed magnitude biases in maneuver executions were removed either through a flight parameter change or within the maneuver design process starting in August 2012. These execution-error model updates are discussed and assessments of maneuver performance following the model and maneuver execution changes are also presented. [View Full Paper]

AAS 13 – 718

(Paper Withdrawn)

AAS 13 – 719

Cloudsat's A-Train Return: Solving the Orbital Dynamics Problem

Barbara Manganis Braun and **Donald Keenan**, The Aerospace Corporation, Albuquerque, New Mexico, U.S.A.

Launched in 2006, NASA's CloudSat mission flew in formation with other earth-observing satellites in NASA's Afternoon Constellation (the "A-Train") until April 2011, when a serious battery anomaly forced CloudSat to lower its orbit and leave the A-Train. Despite the crippled battery, the CloudSat team ultimately restored partial science capability, and plans were made to return CloudSat to the A-Train. CloudSat needed a maneuver plan that would place it in the proper orbit, at the proper position in the A-Train, and at the proper inclination and mean local time of ascending node (MLTAN) relative to CALIPSO, its formation-flying partner, while simultaneously re-shaping its orbit to meet the desired frozen-orbit requirements. But choices of maneuver times and locations were limited, both by CloudSat's synodic period with respect to the A-Train, and also because each tangential (along-track) maneuver would impact CloudSat's eccentricity, and thus its frozenness. CloudSat's maneuverability was also limited by its damaged battery, which could only support maneuvers on the daylight side of the orbit. This paper discusses the CloudSat A-Train return problem in eccentricity space, and presents the equations used to describe the impact of tangential maneuvers (orbit raises and orbit lowers) on CloudSat's eccentricity vector. The paper further discusses how the equations were incorporated into a spreadsheet allowing maneuver plans to be evaluated quickly, which proved critical during the many revisions of the plan. Finally, the paper describes how all the requirements and constraints were balanced to produce a maneuver sequence that successfully returned CloudSat to the A-Train by the summer of 2012. [View Full Paper]

AAS 13 – 720

Post-Maneuver Collision Probability Estimation Using Polynomial Chaos

Brandon A. Jones and **Nathan Parrish**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **Michael S. Werner**, Department of Mechanical Engineering, Colorado School of Mines, Golden, Colorado, U.S.A.; **Alireza Doostan**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

This paper describes the use of polynomial chaos for approximating the probability of a collision between two satellites after at least one performs a translation maneuver. Polynomial chaos provides a computationally efficient means to generate an approximate solution to a stochastic differential equation without introducing any assumptions on the a posteriori distribution. The stochastic solution then allows for orbit propagation uncertainty quantification. For the maneuvering spacecraft in the presented scenarios, the polynomial chaos expansion is sparse, allowing for the use of compressive sampling methods to improve solution tractability. This paper first demonstrates the use of these techniques for the Magnetospheric Multiscale mission, which must regularly assess collision risks between the spacecraft in the formation. The techniques are then applied to a potential collision with debris in low Earth orbit. Results demonstrate that these polynomial chaos-based methods provide a Monte Carlo-like estimate of the collision probability, including adjustments for a spacecraft shape model, with only minutes of computation cost required. [View Full Paper]

AAS 13 – 854

A Homotopy Method for Optimal Actuator Failure Control

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

Most spacecraft are designed to be maneuvered to achieve pointing goals. This is generally accomplished by designing a three-axis control system, which can achieve arbitrary maneuvers, where the goal is to repoint the spacecraft and achieve a desired attitude and angular velocity at the end of the maneuver. New control laws are required, however, if one of the three-axis control actuators fails. The existing state-of-the-art strategies do not provide efficient solutions of this under-actuated nonlinear control problem. This paper develops a homotopy algorithm to achieve optimal nonlinear maneuver strategies minimizing quadratic torque for large-angle three-axis spacecraft reorientation maneuvers. As a benchmark for the nominal case, the solution strategy first solves the three-axis control case when all three actuators are available. The failed actuator case is recovered by introducing a homotopy embedding parameter, ε, into the nonlinear dynamics equation, where the factor, $1 - \varepsilon$, multiplies the actuator control input that is assumed to fail. By sweeping the homotopy embedding parameter, a sequence of neighboring optimal control problems is solved, which starts with the original maneuver problem and arrives at the solution for the failed actuator case. As the homotopy embedding parameter approaches 1, the designated actuator no longer provides the control input to the spacecraft, effectively modeling the failed actuator condition. This problem is complex for two reasons: (i) the governing equations are nonlinear and (ii) the homotopy embedding parameter fundamentally alters the spacecraft's controllability. Given the strength of these nonlinearities, Davidenko's method is introduced for developing an ordinary differential equation for the costate variable as a function of the homotopy embedding parameter. For each value of the homotopy embedding parameter, the initial conditions for the costates are iteratively adjusted so that the terminal boundary conditions for the three-dimensional maneuver are achieved. Optimal control applications are presented for both rest-to-rest and motion-to-rest cases, which demonstrate the effectiveness of the proposed algorithm. [View Full Paper]

SESSION 3: NONLINEAR MODELING AND ANALYSIS METHODS
Chair: James Turner, Texas A&M University

AAS 13 – 721

A Simple Perturbation Algorithm for Inverting the Cartesian to Geodetic Transformation

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

A natural geometric perturbation variable is identified as the ratio of the major and minor Earth ellipse radii minus one. A singularity-free perturbation solution is presented for inverting the Cartesian to Geodetic transformation, which yields millimeter accuracy throughout the LEO through GEO range of satellite applications. Geocentric latitude is used to model the satellite ground track position vector. Rapidly converging perturbation solutions are developed for the satellite height above the Earth and the geocentric latitude as a perturbation power series in the geometric perturbation variable. Very compact series coefficients are recovered for the fourth order series approximations. The perturbation solution algorithm presented in this work provide three significant benefits over existing approaches for the problem: (1) No highly sensitive quartic polynomial solution algorithms are required; (2) A non-iterative algorithm inverts the transformation without requiring special starting guesses for the power series solution; and (3) Uniform solution accuracy is obtained for the Equator and the Polar regions. Simulation results are presented that compare the solution accuracy and algorithm performance for applications spanning the LEO-to-GEO range of missions. [View Full Paper]

AAS 13 – 722

Proper Averaging Via Parallax Elimination

Martin Lara, **Juan F. San-Juan** and **Luis M. López-Ochoa**, University of La Rioja, 26004 Logroño, Spain

The elimination of the parallax simplification may deprive the simplified Hamiltonian of the geopotential from some long-period terms of the second order of J_2, thus, making the achievement of a mean elements orbit whose long-period effects are the same as in the osculating orbit unsuccessful. We show how the separation of short- and long-period variations is improved by choosing properly the generating function of the elimination of the parallax transformation. [View Full Paper]

AAS 13 – 723

An Analytical Approach to Computing Step Sizes for Finite-Difference Derivatives

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Most numerical optimization methods require a derivative to determine search directions and magnitudes, and the prevailing method of computing these derivatives is the finite-difference approximation. While computationally straightforward, a finite-difference approximation requires estimation of a step-size parameter. An algorithm is presented here that computes the optimal step size for a finite-difference approximation of an unknown function's derivative. The algorithm's mathematical foundations are derived and numerical examples are given. The computed step size minimizes the combined roundoff and truncation errors in the finite-difference derivative, and the algorithm provides information on the validity of the step size with respect to changes in the independent variables. It is shown that the computed step size is correlated to the true optimal step size by a closed-form equation. The algorithm is also able to compute the function's condition error without additional user input. [View Full Paper]

AAS 13 – 724

Conic Sections By Rational Bézier Functions

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

Conic sections can be considered a subset of rational quadratic Bézier curves. These curves are defined based on three control points and three weights associated with the three control points. First and last control points (*endpoints*) belong to the curve while the middle control point (*midpoint*) is provided at the intersection of the tangents passing at the endpoints. This paper shows that: 1) the weights associated with the endpoints can always be arbitrarily selected, 2) closed-form solutions are provided for the midpoint weight, 3) by changing sign to the midpoint weight, the complementary part of the conic section is described, and 4) the closed-form expressions of the midpoint weight is an only function of the variation of the eccentric/hyperbolic anomaly of the endpoints. These results are mathematically demonstrated and are provided for all three different conic sections: ellipse, parabola, and hyperbola. Numerical examples are also given to show these new findings on conic sections, which make potential applications in astrodynamics possible. [View Full Paper]

AAS 13 – 725

F And *G* Taylor Series Solutions to the Stark Problem With Sundman Transformations

Etienne Pellegrini, **Ryan P. Russell** and **Vivek Vittaldev**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.

The classic *F* and *G* Taylor series of Keplerian motion are extended to solve the Stark problem and to use the generalized Sundman transformation. Exact recursion formulas for the series coefficients are derived, and the method is implemented to high order via a symbolic manipulator. The results lead to fast and accurate propagation models with efficient discretizations. The new *F* and *G* Stark series solutions are compared to the Modern Taylor Series (MTS) and 8th order Runge-Kutta-Fehlberg (RKF8) solutions. In terms of runtime, the *F* and *G* approach is shown to compare favorably to the MTS method up to order 18, and both Taylor series methods enjoy approximate order of magnitude speedups compared to RKF8 implementations. Actual runtime is shown to vary with eccentricity, perturbation size, prescribed accuracy, and the Sundman power law. The effects of the generalized Sundman transformation on the accuracy of the propagation are analyzed, and the results are valid for both the Stark and Kepler problems. The Taylor series solutions are shown to be exceptionally efficient when the unity power law from the classic Sundman transformation is applied. An example low-thrust trajectory propagation demonstrates the utility of the *F* and *G* Stark series solutions.
[View Full Paper]

AAS 13 – 726

Solving Kepler's Equation Using Implicit Functions

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A new approach to solve Kepler's equation based on the use of implicit functions is proposed here. First, new upper and lower bounds are derived for two ranges of mean anomaly. These upper and lower bounds initialize a two-step procedure involving the solution of two implicit functions. These two implicit functions, which are non-rational (polynomial) Bézier functions, can be linear or quadratic, depending on the initial bound values. These are new initial bounds that have been compared and proven more accurate than Serafin's bounds. The procedure reaches machine error accuracy with no more that one quadratic and one linear iterations, experienced in the "tough range," where the eccentricity is close to one and the mean anomaly to zero. The proposed method is particularly suitable for space-based applications with limited computational capability. [View Full Paper]

AAS 13 – 727

Reflection Decomposition of Rotation Matrices

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Orthogonal matrices are important mathematical objects in astrodynamics mainly because they represent the transformation matrices among reference frames arbitrarily oriented. Examples include spacecraft and planets/moons attitudes as well as the relative orientation of observing instruments with respect to other frames. The fact that the product of two reflections gives an orthogonal matrix is a well known property. Conversely, how to decompose an orthogonal matrix into the product of two reflections is not known. This decomposition is not unique, and this paper provides the whole set of reflection products providing the same orthogonal matrix. This is initially done for the most important 3-dimensional space and it is then extended to any dimensional space. This paper also shows that this decomposition becomes evident in *Geometric Algebra*, which is briefly summarized. The purpose of this paper is to introduce these mathematical properties and to leave the applications to specific problems such as, attitude estimation, kinematics, decomposition of symmetric and skew-symmetric matrices, to future papers. [View Full Paper]

AAS 13 – 728

A Fast and Robust Multiple Revolution Lambert Algorithm Using a Cosine Transformation

Nitin Arora and **Ryan P. Russell**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.

A new universal variable is introduced to improve solution performance for the multiple revolution Lambert problem. The formulation, motivated by the approach of Bate, Mueller and White, is based on the cosine of the change in eccentric anomaly and uses a new geometry parameter to simplify the universal time of flight equation and the associated partial derivatives. Judicious initial guesses and a second order correction step lead to rapid root-solving and a reduction in the number of minimization calls typically required to bound the multiple revolution case. The proposed method is demonstrated to be statistically as accurate as the Gooding method, while achieving 40-60% reductions in runtime. [View Full Paper]

AAS 13 – 729

Improved Uniform Points on a Sphere With Application to Any Geographical Data Distribution

Sanghyun Lee and **Daniele Mortari**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.

This paper describes improved algorithms based on equal-areas spherical subdivision to obtain approximated solutions to the problem of uniform distribution of points on a 2-dimensional sphere, known as Smale's seventh problem. The algorithms provide quasi-uniform distribution points by splitting Platonic solids into subsequent spherical triangles of identical areas. Original equal-areas subdivision algorithm can be applied for a number of points $N = f\,2^s$, where f is based the number of triangles of the Platonic solid considered and s the number of divisions. The main feature of the improved algorithm is that adjacent triangles share common vertices that can be merged as well as to apply reshaping. If a side of the Platonic solid is split into p identical smaller triangles, then the improved method provides $N = p\,f\,2^s$ points. The proposed algorithm is fast and efficient and, consequently, it is suitable for various applications requiring high value of N. The proposed algorithm is then applied to two geographical data distribution that are modeled by quasi-uniform distribution of weighted points. [View Full Paper]

AAS 13 – 730

(Paper Withdrawn)

SESSION 4: SPACECRAFT AUTONOMY AND RENDEZVOUS

Chair: Yanping Guo, Johns Hopkins University Applied Physics Laboratory

AAS 13 – 731

Autonomous Relative Navigation for Spacecraft Rendezvous Based on Celestial Observations and Relative Range Measurements

Kai Wang, **Xinghong Huang**, **Shijie Xu** and **Tong Chen**, School of Astronautics, Beihang University, Beijing, China

This paper provides a novel autonomous relative navigation method based on celestial observations and relative range measurements for far or medium range rendezvous. The chase spacecraft is equipped with a digital imaging sensor and a relative range measuring device. The processing noise model of the relative navigation system is developed based on the spacecraft relative dynamics equations described in the inertial frame. The measurement model on the imaging sensor focal plane and its relations with the target-star angles are studied. A discrete-time EKF is developed to estimate relative states based on the target-star angles and relative distances. Numerical simulations are undertaken to evaluate the performance of the presented filter in comparison with the normal relative navigation filter (using range, azimuth and elevation angles).
[View Full Paper]

AAS 13 – 732

A Robust Control Method of Lunar Orbit Spacecraft Autonomous Rendezvous

Yunyi Hou and **Guangfu Ma**, Department of Control Science & Engineering, Harbin Institute of Technology, Harbin, Heilongjiang, China; **Jianwen Hou**, Shanghai Academy of Spaceflight Technology, Shanghai, China; **Wenlong Li** and **Peng Shi**, School of Astronautics, Beihang University, Beijing, China

The lunar orbital rendezvous is a key technique of lunar return mission. In this paper, the C-W relative dynamic model is established. The virtual target trajectory was segmented designed, allowing the chaser remain at the docking corridor. The H∞ sub-optimal theory was applied in controller design, restraining the interference and over much energy consumption. The mathematical simulation showed that the proposed control method have advantages of high-accuracy, low power consumption, strong robustness and rapidity. Finally, the real-time visualization platform was established to demonstrate the whole process of lunar orbit spacecraft autonomous rendezvous mission. [View Full Paper]

AAS 13 – 733

MPCV ESA Demo-Spacecraft: Mission Design for a Non-Cooperative Rendezvous Demonstration in Elliptic Orbit Around the Moon

Eric Joffre, **Adrien Chapelle**, **Philippe Augros**, **Siegfried Chavy** and **Stephane Reynaud**, EADS Astrium Space Transportation, Les Mureaux, France; **Massimiliano Bottacini** and **Olivier Mongrard**, European Space Agency, Noordwijk, The Netherlands

The European Space Agency proposed to explore, jointly with NASA, the feasibility of a non-cooperative rendezvous demonstration during the MPCV unmanned Exploration Mission 1 to the Moon. This paper describes the study conducted by EADS Astrium on the vehicle and the mission design, with a specific focus on the description of the scenario and of the orbital relative dynamics simulation model. Key characteristics of the spacecraft configuration and of the main functions are also briefly reviewed as a support to the understanding and justification of the mission. [View Full Paper]

AAS 13 – 734

Recursive Update Filter Applied to Spacecraft Rendezvous

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Nonlinear filters are often very computationally expensive and usually not suitable for real-time applications. Real-time navigation algorithms are typically based on linear estimators, such as the extended Kalman filter (EKF). In a typical spacecraft rendezvous very accurate lidar measurements are available to navigate the chaser vehicle with respect to the target. Incorporating these highly accurate nonlinear measurements can cause filter divergence in the presence of highly uncertain initial conditions. This work proposes to use a nonlinear estimator to accurately navigate the chaser vehicle to the target without the need of any *ad hoc* algorithm to keep the EKF consistent.
[View Full Paper]

AAS 13 – 735

A Closed-Loop Solution for Spacecraft Rendezvous Using the KS Transformation

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A closed-loop solution is presented for spacecraft rendezvous using Lyapunov stability theory. The model used is the Kustaanheimo-Stiefel transformation, where the unperturbed equations of motion are equivalent to a simple harmonic oscillator. The chaser spacecraft is allowed to continuously thrust in three-dimensions and there are no restrictions on its initial location with respect to the target. The guidance scheme is performed in two maneuver phases: first, a matching of the target's semi-major axis, and second, a matching of position and velocity of the target. The control algorithm is robust, computationally fast, can be used for both low- and high-thrust problems.
[View Full Paper]

AAS 13 – 736

Autonomous Aerobraking Development Software: Phase 2 Summary

Alicia D. Cianciolo, **Robert W. Maddock**, **Jill L. Prince**, **Angela Bowes**, **Richard W. Powell** and **Joseph P. White**, Atmospheric Flight and Entry Systems Branch (AFESB), NASA Langley Research Center, Hampton, Virginia, U.S.A.; **Robert Tolson**, National Institute of Aerospace, Hampton, Virginia, U.S.A.; **Daniel O'Shaughnessy** and **David Carrelli**, Space Department, Johns Hopkins Applied Physics Laboratory, Laurel, Maryland, U.S.A.

NASA has used aerobraking at Mars and Venus to reduce the fuel required to deliver a spacecraft into a desired orbit compared to an all-propulsive solution. Although aerobraking reduces the propellant, it does so at the expense of mission duration, large staff, and DSN coverage. These factors make aerobraking a significant cost element in the mission design. By moving on-board the current ground-based tasks of ephemeris determination, atmospheric density estimation, and maneuver sizing and execution, a flight project would realize significant cost savings. The NASA Engineering and Safety Center (NESC) sponsored Phase 1 and 2 of the Autonomous Aerobraking Development Software (AADS) study, which demonstrated the initial feasibility of moving these current ground-based functions to the spacecraft. This paper highlights key state-of-the-art advancements made in the Phase 2 effort to verify that the AADS algorithms are accurate, robust and ready to be considered for application on future missions that utilize aerobraking. The advancements discussed herein include both model updates and simulation and benchmark testing. Rigorous testing using observed flight atmospheres, operational environments and statistical analysis characterized the AADS operability in a perturbed environment. [View Full Paper]

AAS 13 – 737

Adaptive Envisioning of Reachable Mission Outcomes for Autonomous Motion Planning at Small Bodies

David A. Surovik and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

An algorithm for efficient reachability analysis of spacecraft mission outcomes is sought to enable autonomous motion planning at close proximity to small bodies. A recent method, which adaptively refines a numerically approximated map between available maneuvers and possible safety outcomes, is extended with a framework for tracking fulfillment of numerous science requirements. Runtime efficiency is greatly improved to facilitate the mapping of mission outcomes on 3D maneuver sets, which are generated for an orbiter of a uniformly rotating triaxial ellipsoid. Visualization tools are developed to ease access of the high-dimensional results, whose complex structure motivates the use of adaptive envisioning. In a preliminary application of these maps, an automated planner is demonstrated to produce mission profiles that safely satisfy several observation goals in a strongly perturbed orbital regime. [View Full Paper]

AAS 13 – 738

Application of LiAISON Orbit Determination Architecture in Navigating a Rover on the Lunar Surface

Siamak Hesar, **Jeffrey S. Parker**, **Ryan M. McGranaghan**, **Jason M. Leonard** and **George H. Born**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **Kohei Fujimoto**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

This paper examines the use of the Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) architecture to perform tracking of a rover on the lunar surface. LiAISON architecture has been demonstrated to achieve accurate absolute orbit determination solutions by processing satellite-to-satellite tracking observations alone. In a novel approach, the LiAISON architecture is applied to perform autonomous navigation of a lunar rover and a satellite in a halo orbit about Earth-Moon L_2 libration point. High-fidelity simulation results show that LiAISON is able to successfully estimate the absolute states of a lunar rover and a halo orbiting satellite simultaneously. [View Full Paper]

AAS 13 – 739

Force Modeling and State Propagation for Navigation and Maneuver Planning for CubeSat Rendezvous, Proximity Operations, and Docking

Christopher W. T. Roscoe, **Jacob D. Griesbach**, **Jason J. Westphal**, **Dean R. Hawes** and **John P. Carrico, Jr.**, Applied Defense Solutions, Inc., Columbia, Maryland, U.S.A.

The state propagation accuracy resulting from different choices of gravitational force models and orbital perturbations is investigated for a pair of CubeSats flying in formation in low Earth orbit (LEO). Accurate on-board state propagation is necessary to autonomously plan maneuvers and perform proximity operations and docking safely. The primary perturbations affecting both absolute and relative orbital dynamics in LEO are expected to be J_2 and drag. However, the effect of drag on the relative dynamics is highly dependent on differences in the ballistic coefficients of the two spacecraft, differences which can be large since the CubeSats are non-symmetric in terms of cross-sectional area for different attitudes. Propagation accuracy is investigated both in terms of the absolute (chief) state and the relative (deputy relative to chief) state. Different perturbing effects are normalized and compared on an order of magnitude basis over a wide range of altitudes and inclinations in LEO, and in detail for a 425 km Sun-synchronous orbit. [View Full Paper]

AAS 13 – 740

Optimal One and Two-Impulse Maneuvers for Relative Satellite Interception and Reconfiguration

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

This paper investigates impulsive maneuver planning for relative satellite motion about either elliptical or circular reference orbits. Problems to intercept an arbitrary final position or reconfigure to an arbitrary final position and velocity, while minimizing the magnitude of the velocity changes, are considered. By specifying the maneuvers to use one or two impulses, respectively, the problem can be reduced to an unconstrained optimization problem for the maneuver times, without requiring solution for the primer vector. Results show the significance of the phasing of the maneuver times relative to the final time. [View Full Paper]

SESSION 5: SOLAR SAILS, TETHERS AND LARGE SPACE STRUCTURES I
Chair: Brent Barbee, NASA Goddard Space Flight Center

AAS 13 – 741

Multibody Modeling of the Attitude Dynamics of Square Solar Sails

Evan Sperber and **Fidelis O. Eke**, Department of Mechanical and Aerospace Engineering, University of California, Davis, California, U.S.A.

A high fidelity multibody dynamics model is developed specifically to study the attitude dynamics of rigid-type solar sails. Nonlinear equations of motion are formed in Autolev with pre-processing code developed in C. An approach for the numerical computation of eigenvalues for a large system of symbolic linear equations is also formulated. Finally, the particular case of passive nutation damping of a spinning body using pendulous dampers is investigated through numerical integration of the nonlinear equations of motion in conjunction with a stability analysis using system eigenvalues.
[View Full Paper]

AAS 13 – 742

A Reorientation Scheme for Large Solar Sails

Bo Fu and **Fidelis O. Eke**, Department of Mechanical and Aerospace Engineering, University of California, Davis, California, U.S.A.

Under solar radiation pressure, the reflective film of a solar sail will sag if one or more of the connecting point is allowed to move. This has been shown to generate enough body torque for the attitude control of a large solar sail. In this paper, a reorientation scheme for large solar sails is developed based on the theoretical development of such an attitude control methodology. Specifically, this paper delineates the algorithmic steps that can be followed to move a large solar sail from one orientation to another. Cases that demonstrate the reorientation scheme are presented. It is found that the proposed scheme can achieve an attitude change of a large solar sail in a timely manner.
[View Full Paper]

AAS 13 – 743

Earth Escape Capabilities of the Heliogyro Solar Sail

Daniel Guerrant and **Dale Lawrence**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.;
Andrew Heaton, Guidance, Navigation, and Control Group, NASA Marshall Space Flight Center, Huntsville, Alabama, U.S.A.

The heliogyro is a spinning solar sail architecture with the sail membrane partitioned into extremely high aspect ratio "blades". It can pitch these blades to generate attitude control moments (similar to a helicopter) or change the direction of thrust. The heliogyro's performance for various Earth escape trajectories is evaluated, accounting for reasonable slew rates and thrust variation during attitude maneuvers. Additionally, several strategies are proposed that improve upon those in the literature. In most cases, the heliogyro's angular momentum is found to be too high to follow Earth escape trajectories that precess its spin axis. Fortunately, an improved escape strategy is found that is 87% as good at the best ideal trajectory, and it does not precess the spin axis. This strategy would escape from geostationary orbit in approximately 150 days.
[View Full Paper]

AAS 13 – 744
(Paper Withdrawn)

AAS 13 – 745

On the High-Precision Steering Law of VSCMGS

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The dynamic model of VSCMGs is established first, then two kinds of work mode are designed according to the torque command: CMG/RW hybrid mode for the large torque situation and RW single mode for the small torque. While work in CMG/RW hybrid mode, besides the conventional singularity avoidance and velocity equilibrium management of the wheels, the steering law also settles the problem of gimbal rate dead-zone nonlinearity through torque compensation by RW sub-mode. While work in RW single mode, the motion of gimbals will be locked. Both the transition process from CMG/RW hybrid mode to RW single mode and the process from RW single mode back to CMG/RW hybrid mode are programmed. During the transition processes, velocity equilibrium of wheels, singularities avoidance of CMG sub-mode and RW sub-mode are considered. A steering law for the RWs under the state of gimbals keeping locked is presented. The RW single mode could reach a better torque precision than the normal CMGs. [View Full Paper]

SESSION 6: EARTH ORBITERS
Chair: Robert Melton, Pennsylvania State University

AAS 13 – 746
The Effect of Different Adsorption Models on Satellite Drag Coefficients

Andrew C. Walker, **Piyush Mehta** and **Josef Koller**, Space Science and Applications, Intelligence and Space Research, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

Accurate satellite drag coefficients are important for reducing orbit prediction errors and for inferring unbiased atmospheric mass density from measurements of satellite decay. Past use of fixed satellite drag coefficients when inferring atmospheric mass density from orbital decay has resulted in large biases in empirical atmospheric models. These biases can be reduced by using physical drag coefficients which model the interaction between the atmospheric gas particles and the satellite surface; however, physical drag coefficients require detailed knowledge of the gas-surface interaction which is most sensitive to the energy and momentum accommodation coefficients. State-of-the-art models reveal that the effective energy accommodation coefficient for satellites in low Earth orbit is strongly correlated with the adsorption of atomic oxygen. Previous work has modeled this dependence using a Langmuir isotherm which works well at altitudes below ~500 km but fails to match data at higher altitudes. Therefore, Freundlich and Temkin isotherms are used here to test whether data at higher altitudes might be better fit with a different adsorption model. Mathematically, both the Freundlich and Temkin isotherms should (and do) better fit the data because they have two free parameters compared to only one for the Langmuir isotherm. Physically, the Freundlich isotherm allows for multi-layer adsorption and an exponential range of adsorption energies corresponding to a non-uniform sur-face. The Temkin isotherm also allows for multi-layer adsorption and accounts for the interaction between the adsorbing gas and the adsorbate whereas the Langmuir isotherm is limited to monolayer adsorption and constant adsorption energy corresponding to a uniform surface. [View Full Paper]

AAS 13 – 747

Uncertainty Quantification of the Orbital Lifetime of a LEO Spacecraft

Lamberto Dell'Elce and **Gaëtan Kerschen**, Aerospace and Mechanical Engineering Department, Liège, Belgium

Orbital lifetime estimation is a problem of great timeliness and importance in astrodynamics. In view of the stochastic nature of the thermosphere and of the complexity of drag modeling, any deterministic assessment of orbital lifetime is likely to be bound to failure. This is why the present paper performs uncertainty quantification of satellite orbital lifetime estimation. Uncertainties in the initial state of the satellite and in the atmospheric drag force, as well as uncertainties introduced by modeling limitations associated with atmospheric density models, are considered. Mathematical statistics methods in conjunction with mechanical modeling considerations are used to infer the probabilistic characterization of these uncertainties from experimental data and atmospheric density models. Monte Carlo propagation is then exploited to achieve a probabilistic description of the orbital lifetime. [View Full Paper]

AAS 13 – 748
(Paper Withdrawn)

AAS 13 – 749

Semi Analytical Implementation of Tesseral Harmonics Perturbations for High Eccentricity Orbits

Vincent Morand, **Albert Caubet** and **Hubert Fraysse**, Space Flight Dynamics Department, CNES, Toulouse, France; **Florent Deleflie** and **Jerome Daquin**, IMCCE / Observatoire de Paris, Université de Lille, Paris, France

In the frame of the French Space Operations Act, CNES addresses the compliance of disposal orbit with the law technical requirement: long term orbit propagation techniques are required. To ensure reasonable computation times, a semi-analytical method has been adopted and implemented in the STELA tool (Semi-Analytical Tool for End of Life Analysis). The paper details the semi-analytical implementation of tesseral harmonics perturbations in STELA, which is valid for high eccentricity orbits. The algorithm is discussed, validation results are given and the impacts of tesseral perturbation on the statistical lifetime distribution of geostationary transfer orbits are presented.
[View Full Paper]

AAS 13 – 750

An Optimization Method for Nano-Satellite and Pico-Satellite Separation Through a Two Mass-One Spring System

Shu Ting Goh, **Zi Rui Lau** and **Kay Soon Low**, School of Electrical & Electonic Engineering, Nanyang Technological University, Singapore

This paper studies the picosatellite ejection system from a nanosatellite, using one spring two mass ejection model. It is desired that both satellites maintain a long communication time after separation though they do not carry propulsion system. Moreover, the picosatellite is required to return to nanosatellite communication range in a given time period. The dynamic motion of the ejection system has been derived. The impact of ejection location, force and direction on the communication and separation time is studied. Results show that a continuous satellite communication could be maintained if the picosatellite is ejected in perpendicular to the flight path direction. However, the possible collision between the two satellites is to be taken into consideration.
[View Full Paper]

SESSION 7: MANEUVER DESIGN
Chair: Ahmad Bani Younes, Texas A&M University

AAS 13 – 751

Geometry of Transformed Variables in the Impulsive Transfer Problem

Thomas E. 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.

Recently a transformation of variables has been used for an object in a Newtonian gravitational field that linearizes the equations of motion. This transformation has been found useful for unconstrained orbital rendezvous and transfer problems.

This paper examines the geometry of these transformed variables for planar orbital transfer problems. The transformed initial, final, and transfer orbits are either points or circles with centers on a horizontal axis. Applied velocity impulses cause horizontal jumps between these points or centers and vertical jumps between points on the circular arcs. [View Full Paper]

AAS 13 – 752

Optimal Open Low-Cost Two-Impulse Transfers in a Plane

Thomas E. 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 finding a planar open optimal two-impulse transfer orbit between two known Keplerian orbits is found in terms of a set of necessary conditions for minimizing the total characteristic velocity of the transfer arcs and a test to pick the minimizing orbit from the extremals. The problem is open in the sense that the difference between the final and initial true anomaly is unbounded.

Using a transformation of the variables presented in previous work, necessary conditions for an optimal transfer are determined, followed by a proof that an optimal transfer exists, concluding with some sufficiency arguments.

Application of the work to non-circular elliptical boundary orbits reveals a set of boundary conditions that result in "low-cost" optimal transfers having velocity increments that are tangent to the boundary orbits at their apogees. These boundary conditions consist of only three types. A simple closed-form solution is provided for each type. More general boundary conditions that result in more complicated optimal solutions are to be discussed in a work that follows. [View Full Paper]

AAS 13 – 753

Impulsive Guidance for Optimal Manifold-Based Transfers to Earth-Moon L1 Halo Orbits

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

An impulsive guidance scheme is presented which maintains the spacecraft on the stable manifold of a L_1 halo orbit in the Earth-Moon system in the presence of thrust errors in the manifold injection maneuver for a 2-impulse ballistic transfer from LEO to the halo orbit. A Monte Carlo analysis is shown for the unguided case using Gaussian input dispersions in burn magnitude and direction to demonstrate the need of impulsive guidance. Two strategies based on the state transition matrix are presented, one using single burns that only target the manifold, and full burn pairs that target the manifold at t_1 and correct velocity errors at t_2. Both strategies effectively reduce the halo orbit insertion miss distances; however, the single burn strategy has lower ΔV costs for guidance. Lyapunov Exponents (Les) of the stable manifold are then obtained and used to determine the best locations to perform the TCMs, which also include similar thrust errors in the final simulations. [View Full Paper]

AAS 13 – 754
(Paper Withdrawn)

AAS 13 – 755

Optimal Earth-Mars Trajectory Control Strategy Design Using Adaptive Genetic Algorithm and Monte Carlo Method

Hou Jianwen and **Zhou Jie**, Shanghai Academy of Spaceflight Technology, Shanghai China; **Hou Yunyi**, Harbin Institute of Technology, Harbin, Heilongjiang, China; **Liu Fucheng**, Shanghai Academy of Spaceflight Technology, Shanghai, China; **He Liang**, Shanghai Institute of Spaceflight Control Technology, Shanghai, China

Trajectory control strategy design is an important work for Mars mission. B-plane differential correction targeting technique is analyzed. In order to optimize the integration index of propellant cost of trajectory control maneuver (TCM) and position precision, the trajectory control strategy is studied by Adaptive Genetic Algorithm (AGA). Comparing with the traditional the traditional numerical method, it can raise the efficiency obviously. At last, delivery statistics for all TCMs is achieved by Monte Carlo (MC) analysis. This paper can be used as a reference a reference to Mars and other interplanetary missions. [View Full Paper]

SESSION 8: ATTITUDE DETERMINATION AND DYNAMICS I
Chair: Renato Zanetti, The Charles Stark Draper Laboratory

AAS 13 – 756

Attitude Motion of a Spinning Spacecraft With Fuel Sloshing in High-G Maneuvers

Lilit Mazmanyan and **Mohammad A. Ayoubi**, Department of Mechanical Engineering, Santa Clara University, Santa Clara, California, U.S.A.

This paper presents the equations of motion of spinning spacecraft with partially-filled, multiple-tanks, a nutation damper, and momentum wheels in the high-g environment. We model the fuel sloshing in each tank by means of two spherical pendulums with torsional dampers at hinge points. Using Kane's method, the nonlinear equations of motion of a spacecraft containing liquid fuel stores are derived. The developed model is an extension of the existing models in the literature. Derived equations of motion of spacecraft are numerically solved and the effects of the slosh-model parameters on the spacecraft nutation angle are investigated. [View Full Paper]

AAS 13 – 757

Fast, Simple and Efficient Asteroid Attitude Propagation by Perturbations

Martin Lara, San Fernando, Spain

A simple rearrangement of the torque free motion Hamiltonian shapes it as a perturbation problem for bodies rotating close to the principal axis of maximum inertia, independently of their triaxiality. The complete reduction of the main part of this Hamiltonian via the Hamilton-Jacobi equation provides the action-angle variables that ease the construction of a perturbation solution by Lie transforms. The lowest orders of the transformation equations of the perturbation solution are checked to agree with Kinoshita's corresponding expansions for the exact solution of the free rigid body problem. For approximately axisymmetric bodies rotating close to the principal axis of maximum inertia, the common case of major solar system bodies, the new approach is advantageous over classical expansions based on a small triaxiality parameter.
[View Full Paper]

AAS 13 – 758

Star Tracker Anomalies: Root Causes and Mitigation Strategies

Austin S. Lee, **Robert J. Kinsey**, **Stephen C. Ringler**, **Brian H. Kawauchi**, **Justin F. McNeil**, The Aerospace Corporation, El Segundo, California, U.S.A.; **Peter C. Lai**, Globalstar Inc., Milpitas, California, U.S.A.

In this paper, results from a recent survey of star tracker anomalies are presented. The star tracker survey task was sponsored by NASA Marshall Space Flight Center's Office of the Chief Engineer. The objective of the survey was to better understand the nature of star tracker anomalies and assist in preventing anomalies to minimize future risks. Star tracker anomaly data was collected from three main sources: The Aerospace Corporation's (Aerospace) Space Systems Engineering Database, Aerospace subject matter experts who have experience with particular star tracker anomalies, and public websites. The collected anomaly data includes 72 cases including many recent and some as far back as 30 years. The data analysis was done using three classification methods: by development phase, by subsystem, and by severity of the anomaly. Among the identified anomalies, the majority were design issues related with software and electronic subsystems. The majority of anomalies were considered minor (e.g., they did not impact mission performance). However, 43% of the anomalies were moderate to major and required corrective actions or had a major impact to the mission (for example, early termination). [View Full Paper]

AAS 13 – 759

Solar Sail Attitude Dynamics Considering Sail Deformation

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The attitude motion of the spinning solar sail IKAROS was unique. Its behavior is highly dependent on the sail deformation, which is flexible and easily changed by the attitude motion itself. It is important, therefore, to understand the relation between the sail deformation and the attitude motion in order to obtain better knowledge of sail design and management. In this study, a consideration is made about how the sail deforms with the centrifugal force on it and its physical stiffness, and how it changes the attitude motion. As a result, the effects of each natural vibration mode of the sail on the attitude motion are formularized. The theory is evaluated using the flight-data of IKAROS and estimating its sail deformation. [View Full Paper]

AAS 13 – 760

Stability of the Relative Equilibria of a Rigid Body in a J_2 Gravity Field

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

The motion of a point mass in the J_2 problem is generalized to that of a rigid body in a J_2 gravity field. Different with the original J_2 problem, the gravitational orbit-rotation coupling of the rigid body is considered in this generalized problem. The linear stability of the classical type of relative equilibria of the rigid body, which have been obtained in our previous paper, is studied in the framework of geometric mechanics with the second-order gravitational potential. Non-canonical Hamiltonian structure of the problem, i.e., Poisson tensor, Casimir functions and equations of motion, are obtained through a Poisson reduction process by means of the symmetry of the problem. The linear system matrix at the relative equilibria is given through the multiplication of the Poisson tensor and Hessian matrix of the variational Lagrangian. Based on the characteristic equation of the linear system matrix, the conditions of linear stability of the relative equilibria are obtained. With the stability conditions obtained, the linear stability of the relative equilibria is investigated in details in a wide range of the parameters of the gravity field and the rigid body. We find that both the zonal harmonic J_2 and the characteristic dimension of the rigid body have significant effects on the linear stability. Similar to the attitude stability in a central gravity field, the linear stability region is also consisted of two regions that are analogues of the Lagrange region and the DeBra-Delp region. Our results are very useful for the studies on the motion of natural satellites in our solar system. [View Full Paper]

SESSION 9: SSA II: PREDICTION AND UNCERTAINTY
Chair: Marcus Holzinger, Georgia Tech University

AAS 13 – 761
Improved Empirical Covariance Estimation

William Todd Cerven, Systems Engineering Division, The Aerospace Corporation, Chantilly, Virginia, U.S.A.

Covariance estimation through a measurement space method can be made more robust by incorporating weights into the least squares solution process. When the measurements are of full rank, it can be shown that the calculation replicates that of a normalized sample covariance calculation. Furthermore, distribution sampling theory can then be used to estimate errors in these covariance estimates. Lastly, this estimator is applied successfully to realistic scenarios where the error distribution is non-Gaussian in Cartesian space. [View Full Paper]

AAS 13 – 762
Efficient Covariance Interpolation Using Blending of Approximate State Error Transitions

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

Efficient storage and quick access to covariance data are important aspects of orbit catalog maintenance and conjunction analysis (CA). The catalog and CA access and storage requirements cannot accommodate running a complete estimation process whenever orbit state and covariance are requested at some time. Instead, ephemeris and reduced covariance data are recorded at discrete times. Covariance interpolation from tabulated data must preserve positive definiteness and evolve covariance similar to the estimation process. This paper describes a new covariance interpolation method which blends approximate state error transitions anchored at end points of interpolation interval to produce accurate physically meaningful covariance. [View Full Paper]

AAS 13 – 763

High-Fidelity Solar Radiation Pressure Effects for High Area-to-Mass Ratio Debris With Changing Shapes

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

In this paper, we investigate the 6 degree-of-freedom motion of high area-to-mass ratio objects (representative of pieces of Mylar insulation) 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. High-fidelity 6 degree-of-freedom simulations are used to investigate the attitude evolution of a constant shape, as well as for objects that flatten out as their spin rate increases. We find that while individual cases may vary to some degree, the main trend that holds is that all objects rapidly spin up about their minimum moment of inertia axis, whether they are allowed to deform or stay constant in shape. [View Full Paper]

AAS 13 – 764

The Effect of Dynamical Accuracy for Uncertainty Propagation

Inkwan Park and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **Kohei Fujimoto**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

A major topic in the field of space situational awareness is to accurately map the uncertainty of an observed object, accounting for nonlinear relative dynamics using either analytic or numerical approaches. For analytic approaches, an open question exists regarding the importance of short-period terms in the analytic theory relative to the secular dynamics terms. This paper will explore this question using the classical Brouwer theory (CBT). Specifically, we discuss how well uncertainty propagation under the secular Brouwer theory (without short-period terms) compares to the CBT, and how the CBT compares to a fully numerical propagation. [View Full Paper]

AAS 13 – 765

Comparison of Multitarget Filtering Methods as Applied to Space Situational Awareness

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

The multitarget tracking problem is fundamental to Space Situational Awareness, and a variety of methods exist to approach it. Conventional methods employ data association algorithms to assign measurements to objects before applying the Kalman filter update equations. Newer methods based in Finite Set Statistics process a set of measurements and update a set of object states without relying on data association. This paper examines several multitarget estimation techniques and applies them to an SSA scenario. Details regarding the theory behind the filters and their implementation are provided, and a numerical simulation is performed to verify the filters' performance.
[View Full Paper]

AAS 13 – 766

Adaptive Split-Merge Algorithm for Gaussian Mixture Models to Solve the Kolmogorov Equation

Kumar Vishwajeet and **Puneet Singla**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

Number of components in a Gaussian mixture model plays an important role in its accuracy and computational complexity. New adaptive split-merge technique is introduced in this paper based on the minimization of error in the solution of Fokker Planck Kolmogorov Equation. We also discuss the effect of splitting/merging of few components on the weights of other components. A single Gaussian component at initial time is split over time to account for the change in the probability density function of the states of the system. [View Full Paper]

AAS 13 – 767

Parallel Track Initiation for Optical Space Surveillance Using Range and Range-Rate Bounds

Christopher W. T. Roscoe, Applied Defense Solutions, Inc., Columbia, Maryland, U.S.A.; **Paul W. Schumacher, Jr.**, Air Force Research Laboratory, Kihei, Hawaii, U.S.A.; **Matthew P. Wilkins**, Applied Defense Solutions, Inc., Columbia, Maryland, U.S.A.

The problem of track initiation is addressed for optical ground or space-based observation of space objects. Angles are the primary quantities available from line-of-sight measurements, but angle rates may also be derived if the data are of sufficient quantity and quality. For a specified rectangular partition in the space of orbital elements, explicit bounds on range and range rate are derived for a given observation based on angles and angle rates. Discretizing the resulting range-range rate hypothesis region allows candidate orbits to be generated in an embarrassingly parallel fashion. The number of hypotheses for track initiation is further constrained by imposing conditions derived from special solutions of Lambert's problem for pairs of observations. Initial results are presented for perfect and noisy simulated data. Also included is an analysis of the sensitivity of the range-range rate bounds with respect to errors in angle rates.
[View Full Paper]

AAS 13 – 768

Refined Orbit Prediction for Catalog Objects

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Lael F. Woods, Navigation and Geopositioning Department, The Aerospace Corporation, El Segundo, California, U.S.A.

Approximately 95% of objects in orbit are inactive. Because of limited tracking resources and a low level of interest, these objects are infrequently tracked and have poor quality predictions with large uncertainties. Thus, satellite owner-operators are faced with numerous close approaches involving low confidence in the location of the inactive object. Consequently, owner-operators either must perform collision avoidance maneuvers more often (reducing mission life and operations) or accept a higher operational risk. This paper describes an algorithm to leverage historical orbital data to increase accuracy in orbit knowledge of inactive objects, and, in turn, provide for more accurate risk assessments. [View Full Paper]

AAS 13 – 769

Investigating the Suitability of Analytical and Semi-Analytical Satellite Theories for Space Object Catalogue Maintenance in Geosynchronous Regime

Srinivas J. Setty, **Oliver Montenbruck** and **Hauke Fiedler**, Deutsches Zentrum für Luft- und Raumfahrt (DLR), German Space Operations Center (GSOC), Wessling, Germany; **Paul J. Cefola**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.; **Martin Lara**, San Fernando, Spain

This paper evaluates the performance of two analytical and one semi-analytical orbit propagation theories for artificial Earth satellites in GEO orbital regime. Computationally efficient propagators are required to maintain a catalogue of space objects, i.e. to determine the orbits of the tracked objects, propagating, and correlating them. Studied theories included are, the Simplified General perturbation theories for deep space (SDP4), Kamel's theory for geostationary objects and the Draper Semi-analytical Satellite Theory (DSST). To test the accuracies of the selected propagators, trajectories are compared with a numerical "truth" trajectory. Computational time and RMS errors are used as comparison metrics. [View Full Paper]

AAS 13 – 770

Comparisons of PHD Filter and CPHD Filter for Space Object Tracking

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

The Probability Hypothesis Density (PHD) filter and the Cardinalized PHD (CPHD) filter are two computationally tractable approximate Bayesian multi-object filters within the Finite Set Statistics framework. The PHD filter estimates the intensity function; the CPHD filter estimates the intensity function and the conditional distribution of the number of objects. The two filters are compared in an example of tracking three space objects, where the CPHD filter is shown to estimate the number of objects as well as the intensity function more accurately. [View Full Paper]

SESSION 10: ORBIT DETERMINATION AND ESTIMATION I
Chair: Puneet Singla, University of Buffalo

AAS 13 – 771

A Linear-Time-Varying Approach for Exact Identification of Bilinear Discrete-Time Systems by Interaction Matrices

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Bilinear systems offer a promising approach for nonlinear control because a broad class of nonlinear problems can be reformulated in bilinear form. In this paper system identification is shown to be a technique to obtain such a bilinear approximation of a nonlinear system. Recent discrete-time bilinear model identification methods rely on Input-Output-to-State Representations. These IOSRs are exact only for a certain class of bilinear systems, and they are also limited by high dimensionality and explicit bounds on the input magnitude. This paper offers new IOSRs where the bilinear system is treated as a linear time-varying system through the use of specialized input signals. All the mentioned limitations are overcome by the new approach, leading to more accurate and less computationally demanding identification methods for bilinear discrete-time models, which are also shown via examples to be applicable to the identification of bilinear models approximating more general nonlinear systems. [View Full Paper]

AAS 13 – 772

Orbit Determination Using Nonlinear Particle Filter and GPS Measurements

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

A particle filter, specifically a Bayesian bootstrap filter algorithm, is applied for estimating the state vector that characterizes the orbit of a satellite, using a set of GPS measurements. The development will be evaluated through performance and computational cost, comparing the bootstrap algorithm results against the unscented Kalman filter (UKF) solution for the same problem. The orbit determination is a nonlinear problem, with respect to the dynamics and the measurements equations. It consists essentially of estimating values that completely specify the body trajectory in the space, processing a set of measurements (pseudo-ranges) related to this body. Such observations are collected through GPS receivers onboard the satellite. The bootstrap filter is proposed for implementing recursive Bayesian filters. It is a statistical, brute-force approach to estimation that often works well for systems that are highly nonlinear. Here, the bootstrap particle filter will be implemented with resampling and roughening, a scheme for combating the reduction in the number of truly distinct sample values.
[View Full Paper]

AAS 13 – 773
(Paper Withdrawn)

AAS 13 – 774

Improving Orbit Determination With Low-Order Fourier Solar Radiation Pressure Models

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

This paper rounds out a series of papers by the authors which explain and demonstrate the use of the Fourier series SRP model for precise orbit determination applications. In particular, this paper presents the mathematical background necessary to use the Fourier model in OD filters. Two numerical examples are given to illustrate the OD performance. First, an empty, spinning upper stage in geosynchronous transfer orbit is presented. Second, we estimate the orbit of a fictional spacecraft orbiter about a small near-Earth asteroid. In all cases, it is shown that the Fourier series model can be estimated for precise orbit fitting, while the standard cannonball model does terribly by comparison. [View Full Paper]

AAS 13 – 775
(Paper Withdrawn)

AAS 13 – 776

LiAISON-Supplemented Navigation of a Crewed Vehicle in a Lunar Halo Orbit

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

This paper offers an early examination of the challenges of navigating a crewed vehicle, with all of the associated unmodeled accelerations that arise from the crew's activities, in an orbit about the Earth-Moon L_2 point. The combination of the unstable nature of libration orbits with the lack of acceleration knowledge makes the station keeping strategy challenging. It is found that a combination of ground tracking and satellite-to-satellite tracking produces the most favorable navigation accuracy. This paper examines the costs and benefits of applying LiAISON (Linked Autonomous Interplanetary Satellite Orbit Navigation) to a crewed mission in an unstable L_2 orbit.
[View Full Paper]

AAS 13 – 777
(Paper Withdrawn)

AAS 13 – 778

Trajectory Determination With Unknown Perturbations

Francesco de Dilectis and **Daniele Mortari**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.;
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In this paper a new approach to estimate the trajectory of a spacecraft based on observations of a known body and on a dynamics environment difficult or impossible to model is presented. One example is observing the Moon in a cislunar trajectory in presence of perturbations difficult to model (solar pressure, pipe leaking, etc.). The trajectory is estimated by a nonrational Bézier function, whose control points and parameters are derived using least-squares. JPL-SPICE and GSFC-GMAT software have been used for simulations. This approach has the advantage of not requiring *any* knowledge of the dynamics, which gives it great generality. The method has been compared with iterative batch least-squares, requiring knowledge of the dynamics and perturbations, and who obtain trajectory estimates by numerical integration of the equation of motion. One motivation is to obtain autonomy for trajectory estimation on cislunar trajectories to guarantee accurate navigation in case of communications loss. While the image processing is the subject of the companion paper, this paper presents an analysis of this new trajectory estimator. [View Full Paper]

AAS 13 – 779
(Paper Withdrawn)

AAS 13 – 780
(Paper Withdrawn)

SESSION 11: DYNAMICAL SYSTEMS THEORY
Chair: John Junkins, Texas A&M University

AAS 13 – 781
(Paper Withdrawn)

AAS 13 – 782

Trajectory Selection Strategy for Tours in the Earth-Moon System

Amanda F. Haapala, **Mar Vaquero**, **Thomas A. Pavlak** and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **David C. Folta**, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

As mission requirements become increasingly complex, improved flexibility in mission design tools is vital. Strategies that offer interactive access to a variety of solutions supply an enhanced perspective of the design space. In this investigation, interactive and automated trajectory design tools are examined for applications in the Earth-Moon system. Operating within a graphical user interface, these tools offer a composite view of multi-body orbits possessing a variety of characteristics, and facilitate the assembly of end-to-end mission designs via interactive selection of trajectory arcs with desirable characteristics. Final designs are imported into NASA's General Mission Analysis Tool for validation and further access in a mission setting.
[View Full Paper]

AAS 13 – 783
(Paper Withdrawn)

AAS 13 – 784

State Transition Tensor Models for the Uncertainty Propagation of the Two-Body Problem

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

Several methods exist for integrating the Keplerian Motion of two gravitationally interacting bodies, even when gravitational perturbation terms are included. The challenge is that the equations of motion become very stiff when the perturbation terms are included, which forces the use of small time steps, higher-order methods, or extended precision calculations. Recently, Turner and Elgohary have shown that by introducing two scalar Lagrange-like invariants that it is possible to integrate the two-body and two-body plus *J2* perturbation term using a recursive formulation for developing an analytic continuation-based power series that overcomes the limitations of standard integration methods. Numerical comparisons with RK12(10), and other state of the art integration methods indicate performance improvements of ~ 70X, while maintaining ~mm accuracy for the orbit predictions. Extensions for *J3* through *J6* are currently under development. With accurate trajectories available, the next important theoretical development becomes extending the series-based solution for the state transition matrices (STM) for both the two-body and two-body plus *J2* perturbation. STMs are useful for many celestial mechanics optimization calculations. Second and third order STM models are developed to support uncertainty propagation investigations. The application of scalar Lagrange-like invariants generates highly efficient state trajectory, STM, and higher-order STMs models. The proposed mathematical models are expected to be broadly useful for celestial mechanic applications for optimization, uncertainty propagation, and nonlinear estimation theory. [View Full Paper]

AAS 13 – 785

Limits of Linear Approximations for Near-Field Approach in EML-2 Libration Orbits

Juliana Feldhacker, **Kevin Ferrant**, **Jeffrey Parker** and **George Born**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.

The Earth-Moon L_2 point is a location of interest as a destination for many future space missions. To date, though, space exploration has only entailed rendezvous maneuvers between vehicles in low Earth and low lunar orbit, dynamical systems based largely on two-body equations of motion. These experiences do not translate well to orbits near L_2 that are governed by the gravity of two massive bodies. This paper explores the use of linear approximations to estimate the ΔV required to rendezvous two spacecraft in the same halo orbit at L_2 in the Circular Restricted Three-Body Problem. The results show that the quality of the linear estimate is a function of the orbit size, location of the target spacecraft within the orbit, and time over which the rendezvous is to occur but is independent of the local stability of the spacecraft's orbit and mostly insensitive to the initial separation between the vehicles. Ultimately, when a mission falls within the linear regime, the linear estimate is an effective and computationally inexpensive means of performing ΔV budgeting in the initial phases of mission design.
[View Full Paper]

AAS 13 – 786

Powered Heteroclinic, Homoclinic Connections Between the Sun-Earth Triangular Points and Quasi-Satellite Orbits for Solar Observations

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

Investigation of new orbit geometries exhibits a very attractive behavior for a spacecraft to monitor space weather coming from the Sun. Several orbit transfer mechanisms are analyzed as potential alternatives to monitor solar activity such as a sub-solar orbit or quasi-satellite orbit and short and long heteroclinic and homoclinic connections between the triangular points L_4 and L_5 and the collinear point L_3 of the Circular Restricted Three-Body Problem (CRTBP) in the Sun-Earth system. [View Full Paper]

AAS 13 – 787

Broad Search for Unstable Resonant Orbits in the Planar Circular Restricted Three-Body Problem

Rodney L. Anderson and **Gregory Lantoine**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.;
Stefano Campagnola, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

Unstable resonant orbits in the circular restricted three-body problem have increasingly been used for trajectory design using optimization and invariant manifold techniques. In this study, several methods for computing these unstable resonant orbits are explored including flyby maps, continuation from two-body models, and grid searches. Families of orbits are computed focusing on the Jupiter-Europa system, and their characteristics are explored. Different parameters such as period and stability are examined for each set of resonant orbits, and the continuation of several specific orbits is explored in more detail. [View Full Paper]

AAS 13 – 788

Exploration of the Structure of the Web of Commensurabilities Within the MEO and GTO Regions

F. Deleflie, **A. Bourgoin**, **J. Daquin**, **A. Vienne**, and **M. Fouchard**, IMCCE / Observatoire de Paris, Université Lille 1, Paris, France.;
E. M. Alessi and **A. Rossi**, IFAC-CNR, Sesto Fiorentino (FI), Italy.; **V. Morand** and **D. Hautesserres**, Centre National d'Etudes Spatiales, Toulouse, France.

We deal with the structure of the web of commensurabilities in the MEO and GTO regions, in a model accounting for the non spherical shape of the Earth, the luni–solar perturbations and the solar radiation pressure. In particular, we study to what extent the change of initial parameters of storage orbits (namely and mainly the semi–major axis and the eccentricity), can affect the long term stability of these orbits over very long time scales (typically, one century). The study is based on the numerical integration of the averaged equations of motion, with a semi-analytic model suitable for all dynamical configurations that has been approved to be the reference one for the French Space Operations Act (through the dedicated software STELA and its Fortran prototype).

In this paper, we present maps of maximal variations of the orbital parameters that we realized in different dynamical configurations, and in particular a couple of ones standing for some representatives cases of operational or disposal orbits in the GTO and MEO regions. We analyze them in terms of detection of resonance areas.
[View Full Paper]

AAS 13 – 789

Connecting Halo Orbits to Science Orbits at Planetary Moons

Kevin A. Bokelmann and **Ryan P. Russell**, Department of Aerospace and Engineering Mechanics, University of Texas, Austin, Texas, U.S.A.

Increasing interest in planetary moons such as Europa calls for capturing into low-altitude science orbits. In this study, the maneuver costs for this final phase are investigated. Analytic expressions are developed to predict the minimum velocity change to transfer between loosely captured orbits and low-altitude science orbits at different energy levels. The equations are derived in both the restricted three-body problem and the Hill's approximation. Visualizations of the results are developed to allow rapid assessment of transfer propulsive costs of interest. Multiple impulsive transfers are calculated to validate the theory. [View Full Paper]

AAS 13 – 790
(Paper Withdrawn)

AAS 13 – 831

Earth Coverage From Earth-Moon Libration Point Orbits

Kathryn E. Davis, **Nathan Parrish** and **George H. Born**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.;
Eric Butcher, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.

Visibility of the Earth's surface by spacecraft in Earth-Moon Libration Point Orbits (LPOs) at L_1 and L_3 is examined. Coverage is computed for single satellites and constellations of spacecraft. Initially, coverage is analyzed in the model formulated by the Circular Restricted Three-Body Problem. Coverage is also computed in the full ephemeris. A constellation consisting of one spacecraft in an L_1 orbit and two spacecraft in reciprocal northern/southern L_3 orbits can provide nearly continuous global coverage of the Earth's surface. [View Full Paper]

SESSION 12:
FORMATION FLYING AND RELATIVE MOTION I
Chair: Craig McLaughlin, University of Kansas

AAS 13 – 791

Orbital Maneuver for Spacecraft Using Generalized Canonical Transformation

Yuki Ohtsuka and **Kenji Uchiyama**, Department of Aerospace Engineering, Nihon University, Funabashi, Chiba, Japan

This paper describes a method of orbit generation and control using generalized canonical transformations of nonlinear dynamics to describe the relative motion of two satellites. A current problem is that a spacecraft's orbit in a circular restricted three body system depends on the initial state of the system. It is difficult to treat both the potential energy, *e.g.* a perturbation of J_2, and the nonlinearity directly when designing a control system for an orbital maneuver. To solve these problems in various missions, we propose a theory of orbit stabilization using generalized canonical transformations. Numerical simulations of formation flying and rendezvous orbits achieved using the proposed control method are demonstrated. [View Full Paper]

AAS 13 – 792

(Paper Withdrawn)

AAS 13 – 793

State Transition Matrix for Relative Motion Including Higher-Order Gravity Perturbations

Hui Yan, **Srinivas R. Vadali** and **Kyle T. Alfriend**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

This paper extends the prediction accuracy of the Gim-Alfriend-J_2-based state transition matrix (GA STM) by including higher-order gravity perturbations due to J_2^2, J_4, and J_6. In lieu of an analytical mean-to-osculating element transformation, consistent initial osculating elements for a given set of mean elements are obtained by a least squares approach. Numerical results show that the extended GA STM is more accurate than its original version, with a remarkable reduction obtained in the cross-track, over the J_2 model. It is observed that the along-track relative motion error does not monotonically decrease as the higher-order effects are included incrementally. These results are validated by the simulation package GMAT. [View Full Paper]

AAS 13 – 794

Formation Control Problems for Decentralized Spacecraft Systems

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

This paper investigates controlling spacecraft formations, as opposed to individual spacecraft in formation, with the intent to determine whether Leader-Follower formations are error- or fuel-optimal. An formation optimal control problem is developed wherein formation slots and spacecraft barycenter weights are the formation control variables. Restricted formation control problems are presented which investigate the effect of controlling the individual spacecraft barycenter weights based on minimum Lyapunov formation error and also based on minimum fuel costs. It is shown that a Democratic formation works well with no *a-priori* knowledge of the formation state or orbit elements. Further, detailed simulation results suggest that Democratic formations tend to have lower overall fuel usage than strict Leader-Follower formations. Conclusions and future work are discussed. [View Full Paper]

AAS 13 – 795

Semi-Analytical Global Search Algorithm for Fuel-Optimal Satellite Formation Reconfiguration: Impulsive-Thrust Approach

Youngkwang Kim, **Sang-Young Park** and **Chandeok Park**, Astrodynamics and Control Laboratory, Department of Astronomy, Yonsei University, Seoul, Republic of Korea

This paper addresses the optimal impulsive control problem of the coplanar formation reconfiguration in a near-circular orbit using impulsive-thrust. This paper introduces a semi-analytical approach of primer vector analysis. For three or four-impulse transfers, semi-analytical solutions of optimal primer vector histories are derived from the necessary conditions of local optimality. The semi-analytical approach is different from the conventional heuristic primer vector analysis in that it utilizes the semi-analytical solutions of optimal primer vector histories. This approach reduces the number of unknown transfer parameters because the necessary conditions of optimality are already satisfied. If the solution exists, boundary conditions determine remaining unknown transfer parameters for given optimal primer vector history. Based on the semi-analytical approach, a global search algorithm has been developed to find global optimal solutions. Various simulations demonstrate that the semi-analytical global search algorithm discovers global optimal solutions satisfying the well-known Lawden's necessary conditions. Moreover, it is found that two different approximate solutions satisfy Lawden's necessary conditions. [View Full Paper]

AAS 13 – 796

Calibration of Hill-Clohessy-Wiltshire Initial Conditions for Elliptic Relative Motion

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

The relative motion between chief and deputy satellites in close proximity with orbits of arbitrary eccentricity can be described by linearized time-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. Three transformations derived from Lyapunov-Floquet theory and an integral-preserving transformation have previously been determined which relate the time-varying equations of motion to the HCW equations. These transformations are used as a method for selecting initial conditions to approximate elliptic relative motion using the HCW equations with far greater accuracy than the true initial conditions. [View Full Paper]

AAS 13 – 797

Techniques for LEO Constellation Deployment and Phasing Utilizing Differential Aerodynamic Drag

Tiffany Finley, **Debi Rose** and **Jillian Redfern**, Southwest Research Institute, Boulder, Colorado, U.S.A.; **Kyle Nave**, Applied Defense Solutions, Columbia, Maryland, U.S.A.; **William Wells** and **Randy Rose**, Southwest Research Institute, San Antonio, Texas, U.S.A.; **Chris Ruf**, Space Physics Research Laboratory, College of Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.

The Cyclone Global Navigation Satellite System (CYGNSS) mission is a recently selected NASA Earth Venture investigation seeking to improve tropical cyclone (TC) modeling and prediction through remote sensing observation of the ocean surface winds in the TC inner core with a LEO constellation of 8 microsatellites. An initial study investigated trades and techniques for the deployment, initial phasing, maintenance, and collision avoidance of the satellite constellation, using differential drag as the only means of orbit modification, to reach an evenly spaced coplanar configuration for the 8 satellites in a circular orbit. This paper reviews these trades and outlines the current CYGNSS mission design. [View Full Paper]

AAS 13 – 798

On Control of Spacecraft Relative Motion in the Case of an Elliptic Keplerian Chief

Morad Nazari and **Eric A. Butcher**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.;
Afshin Mesbahi, Department of Electrical Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.

In this study, control strategies based on time-varying LQR, Lyapunov-Floquet transformation (LFT), backstepping, feedback linearization, and constant gain feedback control are implemented for the linearized time periodic equations of spacecraft relative motion when the reference orbit is elliptic. Also, natural and nonnatural leader-follower two-spacecraft formations are studied. The stability of the closed-loop response, the control effort required, and the settling time are investigated and compared for all control strategies. Furthermore, using constant gain feedback, the estimated region of attraction of the closed-loop system is obtained analytically. [View Full Paper]

AAS 13 – 799

Formation Flying Along an Elliptic Orbit By Pulse Control

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The linearized equations of relative motion of a follower satellite with respect to the leader in a given elliptic orbit are described by Tschauner-Hempel (TH) equations. In this paper, formation flying for the TH system with pulse control input is considered. First, the reconfiguration problem where the desired relative orbit of the follower is natural periodic orbit. Next, the active formation problem where the desired relative orbit is generated by an exosystem is considered. This allows for flexibility of the shape and period of the reference orbit. To realize such a formation flying, the output regulation theory for linear periodic systems is employed. To achieve asymptotic tracking, stabilizing feedback controls are designed by the periodic solution of discrete-time Riccati equation of the linear quadratic regulator (LQR) theory. [View Full Paper]

AAS 13 – 800

Continuous-Thrust Control of Satellite Relative Motion in Elliptic Orbits Using a Lyapunov-Floquet Generalization of the HCW Equations

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

This paper proposes a method for continuous-thrust control for satellite formation flying in elliptic orbits. A previously calculated Lyapunov-Floquet transformation relates the linearized equations of relative motion for arbitrary chief eccentricity to the HCW equations. Using a control law based on Lyapunov-Floquet theory, a time-varying feedback gain is computed that drives a deputy satellite toward rendezvous with an eccentric chief. The control law stabilizes the relative motion across a wide range of chief eccentricities. By contrast, an associated constant gain control law is unstable for high eccentricities and uses more control effort for near-circular orbits. [View Full Paper]

SESSION 13: INTERPLANETARY MISSION DESIGN AND CONCEPTS
Chair: Jeffrey Parker, University of Colorado - Boulder

AAS 13 – 801

Design of Initial Inclination Reduction Sequence for Uranian Gravity-Assist Tours

Nathan J. Strange, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Damon F. Landau**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **James M. Longuski**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

Although a gravity-assist tour of the Uranian moons would be desirable component of a Uranus mission, such tours are especially challenging due to its distance from the Sun and the planet's very high obliquity (97.77º). The high obliquity means that the initial orbits at Uranus tend to be very highly inclined (60º–80º), except in the rare case of arrival during the Uranian equinox (the equinoxes occur every 42 years, with the next one in 2049). The long flight time to Uranus means that there may be precious little time left in a mission for inclination reduction flybys to reach the Equatorial plane. This paper presents a method for the design of the initial capture orbit maneuvers to target a satellite v_∞ that allows for an efficient gravity assist inclination reduction sequence. We also provide an example case for a 2025 mission with a 13-year trajectory to Uranus, a 1-year inclination reduction sequence, and a 2.5 km/s total mission ΔV. [View Full Paper]

AAS 13 – 802

Mission Opportunities to Trans-Neptunian Objects – Part III, Orbital Capture, Low-Thrust Trajectories and Vehicle Radiation Environment During Jovian Flyby

Jordan Kreitzman, **Charles W. Stewart**, **Ethan Cansler**, **Jake Brisby**, **Matthew Green** and **James Evans Lyne**, University of Tennessee, Knoxville, Tennessee, U.S.A.

Our group has previously described high-thrust mission opportunities to a number of trans-Neptunian Objects, including Sedna, Eris, Makemake, Haumea, Huya, Ixion, Varuna, Quaoar and others. In the current study, we extend that work to examine the possibility of orbital capture, and compare the merits of high-thrust and low-thrust primary propulsion systems in terms of the overall mission performance and potential orbital capture mass. In all cases, the outbound trajectory includes a Jovian flyby; radiation exposure during the flyby will influence the viability of candidate mission designs. Therefore the Jovian flyby segments are examined in some detail, and radiation dose-depth curves for several trajectories are presented as a means of comparison. For at least four targets, orbital capture of a small satellite (100-380 kg) was found to be feasible, using a high-thrust interplanetary trajectory and a launch on an Atlas V 551 with a Star 48 upper stage. Low thrust trajectories improve overall performance, either by increasing delivered mass or allowing a smaller launch vehicle. [View Full Paper]

AAS 13 – 803

Broad-Search Algorithms for the Spacecraft Trajectory Design of Callisto-Ganymede-Io Triple Flyby Sequences From 2024-2040, Part I: Heuristic Pruning of the Search Space

Alfred E. Lynam, Mechanical and Aerospace Engineering Department, West Virginia University, Morgantown, West Virginia, U.S.A.

Triple flybys of the Galilean moons of Jupiter can capture a spacecraft into orbit about Jupiter or quickly adjust the Jupiter-centered orbit of an already captured spacecraft. Because Callisto does not participate in the Laplace resonance among Ganymede, Europa, and Io, triple flyby sequences involving gravity-assists of Callisto, Ganymede, and Io occur only aperiodically for limited time windows. An exhaustive search of triple-flyby trajectories over a 16-year period from 2024-2040 using "blind" searching would require 8,415,358 Lambert function calls to find only 127,289 possible triple flyby trajectories. Because most of these Lambert function calls would not converge to feasible solutions, it is much more efficient to prune the solution space using a heuristic algorithm and then direct a much smaller number of Lambert function calls to find feasible triple flyby solutions. The novel "Phase Angle Pruning Heuristic" is derived and used to reduce the search space by 99%. [View Full Paper]

AAS 13 – 804

Broad-Search Algorithms for the Spacecraft Trajectory Design of Callisto-Ganymede-Io Triple Flyby Sequences From 2024-2040, Part II: Lambert Pathfinding and Trajectory Solutions

Alfred E. Lynam, Mechanical and Aerospace Engineering Department, West Virginia University, Morgantown, West Virginia, U.S.A.

Triple-satellite-aided capture employs gravity-assist flybys of three of the Galilean moons of Jupiter in order to decrease the amount of ΔV required to capture a spacecraft into Jupiter orbit. Similarly, triple flybys can be used within a Jupiter satellite tour to rapidly modify the orbital parameters of a Jovicentric orbit, or to increase the number of science flybys. In order to provide a nearly comprehensive search of the solution space of Callisto-Ganymede-Io triple flybys from 2024 to 2040, a third-order, Chebyshev's method variant of the p-iteration solution to Lambert's problem is paired with a second-order, Newton-Raphson method, time of flight iteration solution to the V_∞-matching problem. The iterative solutions of these problems provide the orbital parameters of the Callisto-Ganymede transfer, the Ganymede flyby, and the Ganymede-Io transfer, but the characteristics of the Callisto and Io flybys are unconstrained, so they are permitted to vary in order to produce an even larger number of trajectory solutions. The vast amount of solution data is searched to find the best triple-satellite-aided capture window between 2024 and 2040. [View Full Paper]

AAS 13 – 805

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

Kyle M. Hughes, **James W. Moore** and **James M. Longuski**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

Ballistic gravity-assist trajectories to Neptune are investigated with Earth launch dates ranging from the years 2020 to 2070. One impulsive maneuver is allowed, with up to 3 km/s ΔV, for trajectories that are unable to reach Neptune ballistically. Trajectories are identified using patched-conic techniques with an analytic ephemeris. Classical flyby sequences (e.g. Venus-Earth-Earth-Jupiter), as well as less conventional sequences (that may include flybys of Saturn or Uranus), are considered and compared. Trajectories are constrained to flight times of 15 years or less, and desirable trajectories with regard to parameters such as time of flight, launch date, launch V_∞, arrival V_∞, and ΔV cost are selected and discussed. Of the 76 paths investigated, 21 were found to produce trajectories that satisfied the constraints of this study. The more desirable of these trajectories include a flyby of Jupiter; however, for launch dates when Jupiter is unavailable (such as around 2022 to 2030), direct launch to Neptune or a flyby of Saturn can be used at the cost of a larger ΔV at launch. [View Full Paper]

AAS 13 – 806
(Paper Withdrawn)

AAS 13 – 807
Preliminary Analysis of Establishing Cycler Trajectories Between Earth and Mars Via Low Thrust

Blake A. Rogers and **James M. Longuski**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

While advantages of cycler trajectories are discussed by researchers in the literature, little attention has focused on the problem of placing cycler vehicles into well-known cycler trajectories. Previously, an analysis employing V_∞ leveraging was addressed. The current paper completes the picture by considering the use of low thrust. The most significant result of the present analysis is that the establishment of the Aldrin cycler, the VISIT cycler, and the two-synodic-period cyclers each require surprisingly low amounts of propellant, ranging from 5 to 8 metric tons (mt), after Earth escape for a 95 mt cycler vehicle. Earth escape is accomplished by circular spiral, requiring 15.5 mt of propellant. These values represent a significant mass savings over what is required for V_∞ leveraging. [View Full Paper]

AAS 13 – 808
Optimal Round-Trip Trajectories for Short Duration Mars Missions

David Folta, **Brent W. Barbee**, **Jacob Englander** and **Frank Vaughn**, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Tzu Yu Lin**, Mechanical and Aerospace Engineering Department, University of Florida, Gainesville, Florida, U.S.A.

We describe techniques and results for computing optimal (minimum Initial Mass in Low Earth Orbit (IMLEO)) round-trip trajectories to Mars with total mission duration no greater than one year. The trajectory options surveyed include direct trajectories between Earth and Mars, as well as trajectories that include a Venus gravity assist flyby on the way to Mars, on the way back to Earth, or both. The method of embedded trajectory grids is used to identify the optimal round-trip trajectory solutions without Venus flybys, while a genetic algorithm is employed to identify the optimal solutions that include Venus. The IMLEO required for the mission is further reduced by modeling a pre-positioning of Earth return propellant at Mars via lower energy trajectories in advance of the human portion of the mission, as well as assuming the use of On-Orbit Staging (OOS) in the propulsion system design. Optimal trajectory design results are presented for an array of cases that span ranges of values for various key design parameters including thruster specific impulses, human spacecraft dry mass, and maximum permissible Earth atmospheric entry speed. [View Full Paper]

AAS 13 – 809
(Paper Withdrawn)

AAS 13 – 810
A High Earth, Lunar Resonant Orbit for Lower Cost Space Science Missions

Joseph W. Gangestad, **Gregory A. Henning** and **Randy Persinger**, The Aerospace Corporation, El Segundo, California, U.S.A.; **George R. Ricker**, MIT Kavli Institute for Astrophysics and Space Research, Cambridge, Massachusetts, U.S.A.

Many science missions require an unobstructed view of space and a stable thermal environment but lack the technical or programmatic resources to reach orbits that satisfy these needs. This paper presents a high Earth orbit in 2:1 resonance with the Moon that provides these conditions, reached via lunar gravity assist. Analytical guidance and numerical investigation yielded deep insight into this unconventional orbit's behavior, making it possible to select a robust mission design. Solutions are available for a broad range of missions, from smaller Explorer-class missions such as the Transiting Exoplanet Survey Satellite to larger missions that seek lower-ΔV alternatives to traditional Lagrange-point, drift-away, and geosynchronous orbits. [View Full Paper]

AAS 13 – 811
A Proposed Mission to Detect Solar Influences on Nuclear Decay Rates

Blake A. Rogers and **James M. Longuski**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Ephraim Fischbach**, Department of Physics, Purdue University, West Lafayette, Indiana, U.S.A.

Experiments showing a variation of the nuclear decay rates of a number of different nuclei have suggested that the distance between the sample and the Sun is influencing the nuclear decay processes. In order to test this apparent correlation from Terrestrial experiments, a mission is proposed to take various isotopes on a spacecraft that has a large variation in radial distance and return them to Earth. Two different types of trajectories are considered: one with intermediate Venus flybys and one that injects directly into an Earth-resonant orbit. It is shown that each of these types of trajectories have their relative merits with regards to the scientific objective. The suitability of the upcoming Solar Probe Plus and Solar Orbiter missions to perform this experiment is also investigated. [View Full Paper]

SESSION 14: CLOSE-PROXIMITY OPERATIONS NEAR PRIMITIVE BODIES
Chair: Al Cangahuala, Jet Propulsion Laboratory

AAS 13 – 812
Optical Navigation for Rosetta Operations Near Comet Churyumov-Gerasimenko

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This paper presents an overview of the optical navigation methods developed for the near comet operations of the European Space Agency's Rosetta mission. The innovative aspect of this work lays in the challenge of estimating spacecraft position and comet parameters in absence of a-priori knowledge of the comet, in an active environment possibly leading to varying surface features. Navigation results are presented for synthetic images of a simulated body, showing that landmark observation residuals consistent with 1-pixel accuracy can be obtained, starting only from an approximate rotational period estimate and on the basis of purely optical data. [View Full Paper]

AAS 13 – 813
Exploration of a Graph Based Method for Orbital Transfers Near Small Bodies

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This paper explores the applicability of a graph search method that provides low ΔV impulsive transfers between pairs of periodic orbits to small body orbiters. This involves the creation of a database of periodic orbits and transfers that are computed using continuation, optimization routines and dynamical system theory. The challenges associated with this set up are described in the case of a 8th order and degree rotating gravity field modelling 4 Vesta. With these steps completed, a shortest path algorithm is applied to the resulting weighted-edge graph in order to explore the applications and limitations of the method. While the method relies on the previous set up and is limited to simplified dynamics, it enables the creation of complex, multiple impulsive transfers which involve several intermediate periodic orbits. [View Full Paper]

AAS 13 – 814
(Paper Withdrawn)

AAS 13 – 815

Design of Quasi-Terminator Orbits Near Primitive Bodies

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

Quasi-terminator orbits are a class of quasi-periodic orbits around a primitive body that exist in the vicinity of the well-known terminator orbits. The inherent stability of quasi-terminator trajectories and their wide variety of viewing geometries make them a very compelling option for primitive body mapping missions. In this paper, we discuss orbit design methodologies for selection of an appropriate quasi-terminator orbit that would meet the needs of a specific mission. Convergence of these orbits in an eccentric, higher-fidelity model is also discussed with an example mapping orbit design presented for NASA's upcoming OSIRIS-REx mission. [View Full Paper]

AAS 13 – 816

Circular-Orbit Maintenance Strategies for Primitive Body Orbiters

Mark S. Wallace and **Stephen Broschart**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

For missions to smaller primitive bodies, solar radiation pressure (SRP) is a significant perturbation to Keplerian dynamics. For most orbits, SRP drives large oscillations in orbit eccentricity, which leads to large perturbations from the irregular gravity field at periapsis. Ultimately, chaotic motion results that often escapes or impacts that body. This paper presents an orbit maintenance strategy to keep the orbit eccentricity small, thus avoiding the destabilizing secondary interaction with the gravity field. An estimate of the frequency and magnitude of the required maneuvers as a function of the orbit and body parameters is derived from the analytic perturbation equations. [View Full Paper]

AAS 13 – 817

On an Idea About the Method of Absorbing Spin Motion of an Asteroid for Capture

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This paper presents a method to remove the spin of a target asteroid for a capture mission. The idea uses a small robotic spacecraft either launched separately or carried on the larger mother spacecraft. The small spacecraft first winds up a tether around the target asteroid while itself playing the role of a tip mass, as in a Yo-Yo mechanism. The operation may rely on sophisticated robotic technology, and may include the surface mobile agent jettisoned from the spacecraft. [View Full Paper]

AAS 13 – 818

Non-Linear Pulsed Guidance for Asteroid Close-Proximity Operations

Roberto Furfaro, **John N. Kidd Jr.** and **Daniel R. Wibben**, University of Arizona, Tucson, Arizona, U.S.A.

Autonomous close proximity operations (hovering, landing, Touch-And-Go maneuvers) in the low-gravity environment exhibited by asteroids is particularly challenging. A set of non-linear, pulsed guidance algorithms have been developed for spacecraft that are required to execute autonomous closed-loop guidance to a designated point on the asteroid environment. The guidance algorithms development rely on the definition of a Lyapunov-like descent function that has the property of being negative definite along the trajectory defining the motion of the spacecraft. More specifically, we have defined a) a quickest descent pulsed guidance, where at each point along the guided trajectory, one selects a combination of thrusters (on-off mode) that makes the derivative of the descent function as negative as possible and b) a least effort pulsed guidance where one selects the combination of thrusters that ensure the minimum number of pulsing along the guided trajectory. The derived pulsed guidance laws require information about the current state and the target state and generates a class of feedback trajectories that have a built-in proof of global stability. Guidance simulations in asteroid dynamical environment modeling the spacecraft motion around 433 Eros show that the guidance approach is suitable for autonomously targeting positions and velocity during close-proximity operations. [View Full Paper]

AAS 13 – 819

Real-Time State Estimation for Asteroid Close-Proximity Operations Via Lidar Altimetry and a Particle Filter

Brian Gaudet and **Roberto Furfaro**, University of Arizona, Tucson, Arizona, U.S.A.

Current practice for asteroid close proximity operations typically initiates a maneuver from a safe orbit, and then the maneuver is executed open loop, i.e., once the maneuver is initiated, an estimate of the spacecraft's state is not used to correct for errors. A problem with this approach is that extremely accurate modeling of the asteroid's dynamics is required. Moreover, even with accurate modeling, there is still often considerable error between the targeted and actual spacecraft state at the end of the maneuver, making precision touch and go (TAG) and landing maneuvers impossible. Without real-time spacecraft state estimation that can be coupled to a guidance law, there is no way to improve on this state of affairs. This paper demonstrates how such a real-time state estimation algorithm can be constructed using a Rao-Blackwellized particle filter, a laser altimeter, and an asteroid shape model. The state estimation algorithm is coupled with a guidance law, and precision TAG maneuvers on Itokawa and RQ_{36} are demonstrated via Monte Carlo simulations in a high fidelity simulation environment.
[View Full Paper]

AAS 13 – 820

Observer-Based Body-Frame Hovering Control Over a Tumbling Asteroid

Morad Nazari, **Robert Wauson**, **Thomas Critz** and **Eric A. Butcher**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.; **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

Observer-based hovering control over a tumbling asteroid in the body-fixed frame is studied. An extended Kalman filter (EKF) is used to process range measurements from a small collection of ground stations, yielding estimates of the spacecraft state vector and the gravitational parameters of the asteroid assuming a second degree and order gravity field model. The estimated states are used in the optimal feedback control algorithm which consists of two alternatives: time-varying LQR or the Lyapunov-Floquet transformation (LFT) and time-invariant LQR. The closed-loop response of the system and the control effort required are investigated and compared for both control strategies. [View Full Paper]

AAS 13 – 821

Spacecraft Hovering Control for Body-Fixed Hovering Over a Uniformly Rotating Asteroid Using Geometric Mechanics

Daero Lee, **Amit K. Sanyal** and **Eric A. Butcher**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.; **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

A spacecraft hovering scheme over a uniformly rotating asteroid in the asteroid body-fixed frame using geometric mechanics is presented. The configuration space for the spacecraft is the Lie group SE(3), which is the set of positions and orientations of the rigid spacecraft in three-dimensional Euclidean space. The asteroid trajectory, in the form of natural attitude and translational (orbital) motion of a satellite, is assumed to be available through a spacecraft on-board navigation. The spacecraft tracks a desired relative configuration with respect to the asteroid in an autonomous manner. The relative configuration between the spacecraft and the asteroid is described in terms of exponential coordinates on the Lie group of rigid body motions. A continuous-time feedback tracking control using these exponential coordinates and the relative velocities is employed. A Lyapunov analysis guarantees that the spacecraft asymptotically converges to the desired trajectory. Numerical simulation results demonstrate the successful spacecraft hovering control in the asteroid body-fixed frame for a selected uniformly rotating asteroid. [View Full Paper]

SESSION 15: ORBIT DETERMINATION AND ESTIMATION II
Chair: Ryan Russell, University of Texas - Austin

AAS 13 – 822
Uncertainty Characterization for Angles-Only Initial Orbit Determination

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

When no information is known about a satellite's orbit, an initial orbit determination method must be used. Traditionally, this yields only a point solution, with no uncertainty information. This paper proposes that probabilistic information may be derived directly from the initial orbit solution, given measurement error characteristics. This information may be especially useful when observations of the object are very sparse, and any additional information is valuable. In this paper, we examine Gauss's angles-only method. Assuming the noise characteristics of the sensor are known, we estimate an empirical probability density function yielded by combining the required three measurements. [View Full Paper]

AAS 13 – 823
A Performance Based Comparison of Angle-Only Initial Orbit Determination Methods

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

A comprehensive, performance based comparison of classical and recent methods of angles-only initial orbit determination (IOD) is presented. Several algorithms including techniques developed by the authors will be tested against a variety of ground-based and space-based tracking scenarios. The comparisons are focused on how well the IOD method is capable of estimating the shape and orientation of the orbit. Specific single scenarios along with Monte Carlo analysis are performed. Also, the speed of the IOD methods is compared. The number of observations vary from three to multiple depending upon the capability of the algorithm. [View Full Paper]

AAS 13 – 824

Application of Optical Tracking and Orbit Estimation to Satellite Orbit Tomography

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Satellite orbit tomography is shown through numerical simulations to reconstruct the spatially-resolved global neutral density field using only a single ground site. The study assumes a ground site located near Los Alamos, New Mexico, and selects nearly 200 resident space objects in low-Earth orbit as potential tracking targets. Over a chosen six-day time span in 2011, around 50 objects have enough visibilities to be used. A Constrained Admissible Region Multiple Hypothesis Filter (CAR-MHF) is tested for estimating the satellite position, velocity, and drag ballistic coefficients. The CAR-MHF has difficulty estimating the state in these simulations when the assumed density model has large discrepancies compared with the truth model; however, the simulation results provide reasonable estimates of the expected orbit estimation accuracy for the chosen system. Using this information, the tomography is simulated for the remaining objects, and the density field at lower altitudes around 412 km is reconstructed to within several percent of the true time-averaged density values. [View Full Paper]

AAS 13 – 825

Effect of Coordinate Selection on Orbit Determination

James W. Woodburn and **Vincent Coppola**, Analytical Graphics, Inc., Exton, Pennsylvania, U.S.A.

The application of linear estimation techniques to the non-linear problem of orbit determination requires that a linearization about the spacecraft trajectory be performed. This linearization process can be performed in any number of different coordinates. The effect of coordinate selection on the resulting orbit state and orbit state error covariance in batch and sequential estimators is investigated through examination of the mathematics of the estimators and a numerical example. Estimation in equinoctial elements is seen to be preferred to Cartesian coordinates in both batch and sequential estimation when the orbital motion is dominated by two-body dynamics. Means for affecting a change in the estimation coordinates through localized modifications to batch and sequential estimators are identified which allow for simple conversion of an estimator operating in Cartesian coordinates to be equivalent to an estimator operating in equinoctial elements. [View Full Paper]

AAS 13 – 826

The Conjugate Unscented Transform and the Principle of Maximum Entropy for Probability Density Reconstruction: An Application to the Two Body Problem

Nagavenkat Adurthi and **Puneet Singla**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

This paper describes the quantification of uncertainty in a dynamical system by efficiently evaluating the moments of the state probability density function using the recently developed Conjugate Unscented Transform Method. The Conjugate Unscented Transform is a method by which one can evaluate the multidimensional expectation integrals, involving the Gaussian or Uniform probability density function, with fewer points than the equivalent Gaussian Quadratures. The efficacy of the proposed Conjugate Unscented Transform in capturing the higher order moments when compared to Unscented Transform, Gauss-Hermite Quadrature and Monte Carlo random samples is illustrated by means of a simple Two Body Problem involving the Earth and a satellite. Furthermore, these higher order moments are used to capture the non-Gaussian nature of the state probability density function at the required times by the Principle of Maximum Entropy. [View Full Paper]

AAS 13 – 827

Effects of Orbit Ephemeris Error and Limited Data on Density Estimation

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

Precision orbit derived densities have been estimated along the CHAMP and GRACE orbits and been shown to match the low frequency variations in accelerometer derived densities. The precision orbits used previously have accuracies of 5-10 cm compared to satellite laser ranging residuals. This paper examines the effects of different accuracies of orbit data and non-continuous data on density estimation. Random noise of varying levels is added to ephemeris data and/or continuous data is systematically decimated. Density is then estimated and compared to the case with continuous data and no noise added. [View Full Paper]

AAS 13 – 828

Bayesian Inference on Multimodal Distributions From an Interferometer

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

In a radio-frequency interferometer, modeling phase difference (timing) uncertainty with a normal distribution, the posterior probability density function of the direction is multimodal. We treat the probability density function of the direction cosine as a discrete set of disconnected segments, and investigate with a large number of simulated observations, the *Multiple Mode Combinatorial Hypothesis Least Squares* (MMCHLS) technique introduced in a previous paper. By including the χ_2 probability of the least squares fit through the modes with the probabilities of the individual modes, we can compute a probability weight of each combination of modes. We compare the technique with a single-mode (traditional) least squares, and show that it produces much better results than the traditional technique. The effectiveness of threshold choice on mode separation and results from MMCHLS is addressed, and the possibility of baseline length selection to optimize the results raised. [View Full Paper]

AAS 13 – 829

Spacecraft Navigation Using Extrasolar Planetary Systems

George W. Hindman and **Lila B. Glaser**, Keystone Aerospace, Austin, Texas, U.S.A.

Innovative navigation techniques and systems that improve on-orbit Position, Navigation and Timing (PNT) for spacecraft are highly desired. This paper outlines a new spacecraft hardware and software navigation system that allows for standalone calculation of a spacecraft's location by using in situ Doppler spectroscopy observations. This new system provides onboard orbit self determination through use of specialized reference stars that have exoplanetary companions. Over 900 extrasolar planets have been discovered within the past 18 years. Exoplanet motion around a reference star system's barycenter creates a stable, highly predictable natural stellar signal pattern which can be incorporated into a navigation solution. Potential users include civil government and commercial space platforms. [View Full Paper]

AAS 13 – 830

Using Signals of Opportunity in Deep Space Satellite Navigation: Breadth of Coverage and Solution Accuracy

Ryan E. Handzo, **Jeffrey S. Parker** and **George H. Born**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.;
Kenn L. Gold, Research and Development, Emergent Space Technologies, Colorado Springs, Colorado, U.S.A.

This paper considers a new resource for use in satellite navigation: Signals of Opportunity. These are any signals transmitted into a satellite's environment that are not intended to be used for navigation purposes. The most promising Signals of Opportunity, digital television signals, are the focus of this study. This paper studies how often signals may be available for a satellite to use, and how the uncertainty of the signal's estimate of the satellite's orbit evolves with time. These free signals provide a new option for orbit determination for satellites beyond GNSS effectiveness. [View Full Paper]

SESSION 16: ATTITUDE GUIDANCE AND CONTROL

Chair: Don Mackison, University of Colorado – Boulder

AAS 13 – 832

Repetitive Control of Digital Systems Having Fast Phase Change Produced in the Discretization

Benjamas Panomruttanarug, Department of Control System and Instrumentation Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand;
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Repetitive control (RC) can be used for active vibration isolation in spacecraft that have vibration sources such as reaction wheels or CMGs. Previous research developed very effective FIR compensator design methods. These designs tune the FIR gains to make the compensator frequency response be close to the inverse of the digital feedback control system frequency response. Then the RC adjusts the command to the feedback control system aiming to converge to complete elimination of the effects of the periodic disturbance. The discrete time equivalents of continuous time systems fed by a zero order hold have somewhat different frequency response characteristics. We investigate the situations in which the phase response of the discrete time system can have sudden changes in phase approaching ± 90 deg. A phase error of 90 deg is the ideal stability robustness limit of repetitive control systems. It is the purpose of this paper to determine under what conditions discretization produces such large sudden phase changes in the response, and to determine to what extent such changes cause difficulty in producing stable RC designs. It is shown that fast sample rate with even pole excess produces fast phase changes at Nyquist frequency. Also, slow sample rates can produce arbitrarily steep cliffs in the phase plot. However, the RC design process is found to be able to maintain stability, but with possibly very reduced stability margin.
[View Full Paper]

AAS 13 – 833

Investigation of Discrete Time Emulation Techniques to Simplify Repetitive Control Design

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Repetitive control (RC) is a control method specifically designed to eliminate the effects of periodic disturbances on control systems. In spacecraft they can be used for active vibration isolation. The authors and coworkers have developed several simple RC design methods that are somewhat analogous to PID controller design in classical control. From the early days of digital control, emulation methods were developed based on a Forward Rule, a Backward Rule, Tustin's Formula, a modification using prewarping, and a pole-zero mapping method. These allowed one to convert a candidate controller design to discrete time in a simple way. This paper investigates to what extent these methods can be used to simplify RC design. It is shown that the first two methods can work when using an appropriate cutoff of the learning process, and the other methods fail in this application. However, making use of knowledge obtained in RC compensator design, the pole-zero mapping rules can be modified to produce a particularly simple and effective RC design method. [View Full Paper]

AAS 13 – 834

Single-Axis Pointing of a Spacecraft With Two Skew Control Moment Gyros

Haichao Gui, **Lei Jin** and **Shijie Xu**, School of Astronautics, Beihang University, Haidian District, Beijing, P.R. China

The single-axis pointing of a spacecraft using two skew single-gimbal control moment gyros (CMGs) is investigated. First, two types of restrictions are enforced on the gimbal motions of two skew CMGs, with each restriction yielding control torque along a principal axis of the spacecraft. Then, a two-step eigenax rotation strategy, executing by the two single-axis torques respectively, is designed to point a given body-fixed axis along a desired direction. All the body axes that can be pointed toward an arbitrary inertial direction by two single-axis rotations are identified. Moreover, the amplitude of each rotation is analytically derived and CMG singularities are avoided by limiting the maximum slew rate for each rotation. [View Full Paper]

AAS 13 – 835

Feedback Control and Steering Laws for Spacecraft Using Canfield Joint Attitude Manipulators

Eamonn Moyer and **Manoranjan Majji**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

A novel attitude control system using a reaction wheel mounted on a Canfield joint is introduced. The rotational equations of motion for a rigid body spacecraft equipped with a pair of Canfield joint attitude manipulators are derived. Stable feedback laws are developed for attitude control and momentum management of the spacecraft using Lyapunov theory. Steering laws to find the gimbal rates to generate the torque required for a maneuver are derived in both a linear and a nonlinear form. Numerical simulations of a representative spacecraft reorientation maneuver demonstrate the utility of the control and steering laws developed in this research. The singularity problem associated with traditional configurations of single-gimbal control moment gyroscopes is discussed in relation to the attitude control system being presented. [View Full Paper]

AAS 13 – 836

Quaternion Based Optimal Spacecraft Reorientation Under Complex Attitude Constrained Zones

Unsik Lee and **Mehran Mesbahi**, W. E. Boeing of Department of Aeronautics and Astronautics, University of Washington, Seattle, Washington, U.S.A.

The paper addresses quaternion-based energy and time optimal spacecraft reorientation in the presence of complex attitude constrained zones. Designing an optimal reorientation trajectory for a rigid body spacecraft is posed as a nonlinear optimal control problem. In this direction, attitude constrained zones are defined with respect to the onboard instrument under two categories, forbidden and mandatory zones. These zones are parameterized as quadratic inequality constraints in unit quaternions. The optimal control problem is then solved using a Gauss pseudospectral method. Ambiguity on geodesic/non-geodesic rotations which is a consequence of the quaternion formulation, is discussed and a novel algorithm is presented for its treatment. The paper concludes with extensive simulation results including typical scenarios many science mission spacecraft face as well as more complex scenarios in order to demonstrate the viability of the proposed methodology. [View Full Paper]

AAS 13 – 837

Suboptimal Delayed Feedback Attitude Stabilization of Rigid Spacecraft With Stochastic Input Torques and Unknown Time-Varying Delays

Ehsan Samiei and **Eric A. Butcher**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.

This paper addresses the stabilization problem of rigid spacecraft attitude dynamics in the presence of external stochastic torques and an unknown time-varying delay in the measurement. By employing a linear delayed state feedback controller, a suitable Lyapunov-Krasovskii functional, and Ito's differential formula, a delay dependent stability condition in terms of a linear matrix inequality (LMI) is obtained whose solution gives the controller gain matrices. In addition, a quadratic cost function is applied to the derived LMI to achieve a suboptimal control performance for the system. An estimate of the region of attraction of the controlled system is also obtained, inside which the asymptotic stability of system is guaranteed in the mean-square sense. Finally, to show the effectiveness of the proposed controller, a set of simulations are performed on the attitude dynamics of a given spacecraft. [View Full Paper]

AAS 13 – 838

Adaptive Attitude-Tracking Control of Spacecraft With Uncertain Time-Varying Inertia Parameters

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Adaptive control schemes for spacecraft attitude tracking are abundant in controls literature. However, very few are designed to guarantee consistent performance for a spacecraft with both rigid and non-rigid (time-varying) inertia components. Since inertia matrix changes are a common occurrence due to phenomena like fuel depletion or mass displacement in a deployable spacecraft, an adaptive control algorithm that takes explicit account of such information is of significant interest. In the present investigation, a certainty-equivalence based adaptive control scheme is proposed for the attitude control of a spacecraft characterized by a time-varying inertia matrix with known time-variation but unknown bounds. A smooth-projection scheme is implemented to ensure that parameter estimates stay bounded within a convex set. The variable inertia components may have time and/or state dependencies, or may be purely input dependent. Detailed derivations of the control law are provided along with a thorough analysis for the associated stability and error convergence properties. In addition, numerical simulations are presented for a spacecraft experiencing fuel depletion to highlight the performance benefits when compared with an adaptive control scheme that does not account for inertia variations. [View Full Paper]

AAS 13 – 839

Stability Analysis and Sun-Tracking Attitude Control of Spacecraft Under Solar Radiation Pressure

Naohiro Hayashi and **Go Ono**, Department of Aeronautics and Astronautics, Graduate School of Engineering, The University of Tokyo, Bunkyo, Tokyo, Japan;
Yuya Mimasu and **Jun'ichiro Kawaguchi**, Institute of Space and Astronautical Sciences, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

In an interplanetary mission, the influence of solar radiation pressure (SRP) is a dominant disturbance in terms of the attitude control of a spacecraft, and a continuous disturbance may shorten a mission life time. On the other hand, it was observed that a spin axis of a spinning spacecraft under the SRP tracks the Sun direction, and this is called an attitude drift motion The objective of this study is to analyze the stability of a spin motion and an attitude drift motion of a spacecraft generally and quantitatively. This stability analysis enables Sun-tracking attitude control by using the attitude drift motion only with spin rate control. [View Full Paper]

AAS 13 – 840

A Hybrid CMG-RW Attitude Control Strategy for Agile Small Satellites

Kunal Patankar and **Norman Fitz-Coy**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.

This paper discusses a COTS-based momentum exchange devise which operates in a hybrid control moment gyroscope (CMG) and reaction wheel (RW) mode to achieve rapid retargeting as well as precision pointing by selectively using the torque amplification capabilities of the single gimbal CMGs or direct torque capabilities of the flywheel motors. The system switches from CMG to RW mode based the slew rate and the pointing stability requirements. A mathematical model of this hybrid CMG is then developed and practical challenges involved in implementation of such system are discussed. Effectiveness of this system is then shown through simulations.
[View Full Paper]

AAS 13 – 841

Free Floating Space Robot Kinematic Modeling and Analysis

Xinghong Huang and **Shijie Xu**, School of Astronautics, Beihang University, Haidian District, Beijing, P.R. China

A systematic free floating space robot model is established, which demonstrates the motion rate relations between the joint angles and the attitude of the base, and the relations between the joint angles and the position/attitude of the end effector. The modeling process starts from the original definition of linear and angular momentum conservation laws, uses the transformation method of multiple cumulative sum and the tensor projection method as basic tools. Based on the modeling results, choosing a planar space robot as an object for simplicity, a series of profound and comprehensive characteristics analysis and proof of the system are derived, such as the property of nonholonomy, history path dependence and controllability. [View Full Paper]

SESSION 17:
SSA III: ORBIT DEBRIS MODELING AND MITIGATION
Chair: Glenn Peterson, The Aerospace Corporation

AAS 13 – 842

Space Debris as an Epidemic:
Complexity and Dynamical Systems in the Debris Problem

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

We use classical mathematical techniques to examine the stability of nonlinear governing equations which are a super-set of Kessler's equations. We prove that the solutions are unconditionally stable "logistical" attractors with chaotic and unpredictable limiting solution trajectories. This is analogous to a tipping point, but debris growth is not exponential. Behavior during the approach to equilibrium depends on initial conditions, implying that active debris removal should consider the parameters of the more comprehensive nonlinear prescription. Comprehensive numerical simulations of several independent investigators confirm such behavior. This work applies principles and techniques well developed in complexity and dynamical systems. [View Full Paper]

AAS 13 – 843

COBRA: A Covariance-Based Debris Risk Assessment Model

Felix R. Hoots and **Brian W. Hansen**, The Aerospace Corporation, Chantilly, Virginia, U.S.A.

A satellite breakup caused by a hypervelocity impact will create a large number of debris particles. A small portion of these will be large enough (say >10 cm) to be tracked by the Space Surveillance Network (SSN). The vast majority will never be tracked and cataloged. Eventually these small debris particles disperse into a shell around the Earth and can be essentially characterized as an enhancement to the existing debris background. However, prior to this complete spreading, the particles can be described more as a cloud which poses an elevated risk to any spacecraft passing through the cloud. The purpose of this paper is to present a new method for determining the risk posed by the cloud to resident spacecraft using covariance to account for the uncertainty of cloud fragment and satellite locations. [View Full Paper]

AAS 13 – 844

Summarizing the General Effects of Breakup Debris in GEO

Brian W. Hansen, Mission Analysis and Operations Department, The Aerospace Corporation, Chantilly, Virginia, U.S.A.; **Marlon E. Sorge**, Advanced Technology and Concepts, The Aerospace Corporation, Albuquerque, New Mexico, U.S.A.

A major breakup event in GEO could occur at any time due to an explosion or collision of resident space objects. While much research has been done on breakup debris in LEO, where events like this have occurred, relatively little has been done for GEO. This paper seeks to document and build upon several recent studies to further our understanding of debris cloud evolution and expected risk following a GEO breakup. This includes comprehensive analysis of fundamental differences between GEO and LEO debris that affect risk, and parametric analysis indicating which perturbations are most important for GEO debris cloud modeling. [View Full Paper]

AAS 13 – 845

Use of Slowly Varying Orbit Elements for Spread Velocity Reconstruction of Historical Orbital Breakups

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

This paper examines multiple historical explosions and collisions of on-orbit objects to determine their breakup characteristics. These parameters, primarily spread velocity distribution, can be utilized in validation and verification of breakup codes such as IMPACT. Typically this is performed by using debris objects that are identified shortly after the event, but by using slowly varying orbit elements rather than short-term conjunction assessment, debris objects that appear months to years after the event can be effectively included in determining the spread velocity. Results show that both methods yield event breakup characteristics that are very similar in nature. [View Full Paper]

AAS 13 – 846

Space Debris Visualization, Characterization and Volume Modeling

Ryan E. G. McKennon-Kelly and **Felix R. Hoots**, The Aerospace Corporation, Chantilly, Virginia, U.S.A.

This paper presents a method of generating a temporally evolving 3-Dimensional (3D) surface that encloses a collection of orbital debris particles. Previous methods of visualizing space debris were inadequate and often misrepresented the scale of the debris. The method described herein produces a 3D model of the debris cloud, which can then incorporate the use of color and transparency to provide a more accurate visualization of the cloud’s extent, and potential danger to the viewer. The method produces a closed 3D cloud. Therefore computational geometric methods may be applied to determine whether or not a particle is located within the model. This provides an efficient way to quickly determine if a satellite of interest passes through the debris field.
[View Full Paper]

AAS 13 – 847
(Paper Withdrawn)

AAS 13 – 848

Effects of the Rotational Motion of Debris Objects on the Prediction of Their Orbital Motions

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Since the launch of the first satellites, the coupling of translational and rotational motions of non-actively controlled objects moving in relatively low orbits about the Earth has been recognized as an important factor in the calculation of accurate orbits. In the case of debris objects, lack of knowledge of the objects' physical characteristics makes explicitly including the effects of rotational motion difficult. However, simulations based on six-degree-of-freedom models of generic types of debris objects can provide considerable insight into the effects of their rotational motions on their ballistic coefficients and hence their orbital motions. In this paper, we use some analytical models, a six-degree-of-freedom simulation, and a three-degree-of-freedom orbit determination program to study the effects of debris rotational motion on the prediction of the objects' time-varying ballistic coefficients and their orbits. First, uncoupled models for the rotational motion of rigid bodies and for orbital motion that includes the principal effects of the Earth's oblateness are used to demonstrate the variability of ballistic coefficients of objects with simple shapes due to the rotation of the object and the rotation of its orbit. Then, results obtained using the simulation and the orbit determination program are presented to illustrate how simulated and estimated ballistic coefficients differ and the errors produced by poor estimates. [View Full Paper]

AAS 13 – 849

A Mathematical Formulation to Describe Density of Particles in an Inhhomogeneous Distribution

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A mathematical formulation is developed to define the number density of particles distributed in a system that exhibits pronounced clustering in regions whose dimensions are small compared to those of the whole system but yet are large compared to the dimensions of physical systems of interest. This is the case when a spacecraft traverses a cloud of space debris generated from a collision or an explosion at some time after the event has occurred. The problem of describing inhomogeneity also occurs with certain systems of stars or galaxies. It also occurs in cluster determination applicable to pattern classification, artificial intelligence and neural networks. A parameter which is an indication of the coarseness of resolution is introduced to enable the definition of the density in rigorous terms. This parameter is useful in describing the regions of high and low population and also in quantifying the non-uniformities of a distribution of particles. [View Full Paper]

AAS 13 – 850

Orbit Determination of ETS-8 by Pegasus Observatory in Kyushu University

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Orbital debris removal is suggested for sustainable space development and utilization for human being to deal with the recent orbital debris issues. Kyushu University in Japan has operated a Meade telescope since 2012, and started working on investigation of knowledge on how objects to be removed are tumbling using light curve. However, the estimation of attitude motion needs orbit determination first since attitude estimation requires a geometrical relationship among the Sun, the observer, and the target debris. This paper introduces the telescope, presents an established orbit determination tool, and tests the tool by observing ETS-8, a geosynchronous spacecraft. [View Full Paper]

AAS 13 – 851

Space-Based Characterization of Debris in Low-Earth Orbit Via LWIR Imaging

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Every space launch increases the overall amount of space debris, especially when circumstances result in the orbital objects being stranded in orbit with no de-orbiting capabilities. Studies contributing to the understanding of space debris aid spacecraft operators in mitigating risk associated with Earth-orbiting debris objects. Accurately characterizing the debris threat to a spacecraft is of vital importance in maximizing the lifespan and mission capabilities of the spacecraft. This investigation aims to build LWIR radiometric models of typical debris and use these models to develop techniques for detecting and characterizing the debris object by signal analysis of unresolved imagery. [View Full Paper]

SESSION 18: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL
Chair: Dr. Maruthi Akella, University of Texas - Austin

AAS 13 – 852

Heuristic Suboptimal Solutions to Reduce Velocity Pointing Errors for Spinning, Thrusting Spacecraft

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During axial thrusting of a spinning spacecraft, misalignments and center-of-mass offset result in velocity pointing errors. These pointing errors cause the spacecraft to deviate from its desired trajectory. Typically the axial thrust behaves like a step function, jumping from zero to its maximum value. Alternatively, by ramping-up the axial thrust from zero to its maximum value, the velocity pointing errors are significantly reduced compared to those arising from the step function. Various ramp-up profiles are considered to heuristically find a suboptimal solution to minimize the velocity pointing error. The exponential, cosine, and parabolic functions considered all drive the velocity pointing error to nearly zero and hence qualify as optimal solutions (for all practical purposes). [View Full Paper]

AAS 13 – 853

Image Processing of Illuminated Ellipsoid

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This paper presents the image processing algorithms (and associated mathematics) of Moon or Earth pictures taken by a visible camera to accurately measure the direction vector to the observed body (Moon or Earth). Using these vectors from a sequence of images it is then possible to perform initial trajectory estimation in cislunar trajectories. Even though Moon can be considered a sphere and the Earth an axial-symmetric ellipsoid, the presented theory is developed for the general case of three-axis ellipsoid. It is proved that, using a pin-hole camera model, the observed image is a projected ellipse that is obtained as projection of the intersection of an elliptical cone with unit-radius sphere. This paper proves that the direction to the center of the observed ellipse and the direction to the body center are displaced by an offset. The paper shows how to quantify this offset and how to take it into account in the image processing. The equation of the terminator on a three-axis ellipsoid is also derived. High accuracy estimation of body center and radius is obtained by least-squares using circular and elliptical sigmoid functions. A numerical example and a flowchart is provided to clarify the image processing steps. [View Full Paper]

AAS 13 – 855

Thrusters Time-Delayed Control Allocation for Soft-Landing of Lunar Lander

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During the Entry, Descent and Landing (EDL) Phase, the thruster is the main actuator responsible for ensuring a soft landing at the end of the phase. If the lunar lander can generate only a few levels of fixed constant force with a low control frequency, it is difficult to make a soft landing. In order to get a soft landing without changing the non-throttling valve into throttlable hardware system, the modified controller was designed and verified through a simulation. The proposed controller is to introduce time-delayed and allocated control to the set of the assigned thrusters. [View Full Paper]

AAS 13 – 856

Operations Concept, Hardware Implementation and Ground-Test Verification of a Hazard Detection System for Autonomous and Safe Precision Lunar Landing

John M. Carson, **Erik S. Bailey**, **Nikolas Trawny** and **Andrew E. Johnson**, GN&C Hardware and Testbed Development Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **Vincent E. Roback**, Remote Sensing Flight Systems Branch, NASA Langley Research Center, Hampton, Virginia, U.S.A.; **Farzin Amzajerdian**, Laser Remote Sensing Branch, NASA Langley Research Center, Hampton, Virginia; **Robert A. Werner**, Retired, Optical Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Autonomous precision Landing and Hazard detection and Avoidance Technology (ALHAT) project has developed a Hazard Detection System (HDS) for real-time determination of safe landing sites and site-relative navigation during precision landing of a robotic or crewed vehicle. The HDS design was driven by real-time landing-operations requirements to detect 30-cm terrain hazards, locate safe landing sites, and track terrain features under any surface lighting conditions within a 1-hectare region of the Lunar surface starting from a 1-kilometer slant range with a 30º approach angle and a 30-100 m/s descent rate. To achieve the requirements, the HDS constructs in real time a 10-cm resolution Digital Elevation Model (DEM) and processes it through a Hazard Detection (HD) algorithm to determine safe landing sites. Subsequently, the HDS provides Hazard Relative Navigation (HRN) updates that are correlated with the DEM to provide site-relative position measurements. The current-generation HDS hardware implementation consists of a two-axis gimbaled flash Lidar (Light Detection and Ranging) sensor with a 1º Field of View (FOV) lens and a 128 × 128 pixel detector array, a dedicated Inertial Measurement Unit (IMU) and a custom Compute Element (CE). The Lidar narrow-FOV lens is necessary for providing the DEM resolution from images with the current-generation detector, but it also imposes precision control and knowledge requirements on the HDS and vehicle Navigation during HD and HRN. This paper gives an overview of the HDS design implementation and operations concept to meet these challenging operations objectives, as well as details on the rigorous development and ground-testing campaign to calibrate and align the HDS to achieve the necessary precision pointing. This work has been in preparation for flight tests onboard a helicopter and the NASA Morpheus rocket-propelled, terrestrial flight-test vehicle.

[View Full Paper]

AAS 13 – 857

On Six D.O.F Relative Orbital Motion Parametrization Using Rigid Bases of Dual Vectors

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The relative orbital motion is a six d.o.f motion, generated by the coupling of the relative translational motion with the rotational one. This paper is focused on developing a new relative orbital motion parametrization method using dual rigid bases. Our studies showed that, in the dual tensors free module, the dual rigid bases can completely characterize the relative orbital motion from the Euclidean three dimensional space. The combination between a dual rigid basis and its reciprocal provides a natural computational instrument that can be used to solve many problems in the kinematics, dynamics and control of relative orbital motion setups. [View Full Paper]

AAS 13 – 858

Adaptive Position and Attitude Tracking Controller for Satellite Proximity Operations Using Dual Quaternions

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In this paper, we propose a nonlinear adaptive position and attitude tracking controller for satellite proximity operations. This controller requires no information about the mass and inertia matrix of the satellite, and takes into account the gravitational force, the gravity-gradient torque, the perturbing force due to Earth's oblateness, and other constant – but otherwise unknown – disturbance forces and torques. We give sufficient conditions on the reference motion for mass and inertia matrix identification. The controller is shown to be *almost* globally asymptotically stable and can handle large error angles and displacements. Unit dual quaternions are used to simultaneously represent the absolute and relative attitude and position of the satellites, resulting in a compact controller representation. [View Full Paper]

AAS 13 – 859

A Least Squares Solution for Estimation of a Planar Homography

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This paper presents a linear and nonlinear least squares solution to the planar homography problem for pose estimation in vision based navigation system. Applications for the planar homography solution include camera calibration, LADAR system calibration and navigation problems pertaining to relative spacecraft rendezvous and proximity operations. The methodology developed in this paper is employed to provide a navigation system for a quad rotor using passive image features observed using a camera that is mounted on-board the drone. [View Full Paper]

AAS 13 – 860

Halo Orbit Targeting Guidance Via Higher Order Sliding Techniques

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

In this paper, the Multiple Sliding Surface Guidance (MSSG) algorithm has been implemented and simulated to verify the ability to target the insertion point of a suitable halo orbit in the vicinity of the Sun-Earth libration points. Based on Higher-Order Sliding Control (HOSC) theory, the proposed MSSG algorithm computes an acceleration command that target a specified state by considering only knowledge of the current and desired position and velocity. Results show that the guidance scheme is able to successfully target a suitable state for proper orbital insertion. Furthermore, it will be shown how the algorithm can be used to target the L_1 point in the Sun-Earth system. A detailed study has also been performed to investigate the guidance performances as function of the guidance parameters. The global stability of the proposed guidance scheme is proven using Lyapunov-based approach. [View Full Paper]

AAS 13 – 861

Distributed Internet-Enabled Simulation/Testbed Architecture

Marcelo Gonzalez-Oberdoerffer, **Darren Zanon** and **Ravishankar Mathur**, Emergent Space Technologies, Greenbelt, Maryland, U.S.A.

The rising complexity of space mission requirements and robotic operations in space has spawned a number of diverse n-degree of freedom (N-DOF) dynamic hardware testbeds across the country. Examples include air tables, spherical mounts, robotic arms, and many others. While each testbed on its own may only be able to simulate a specific hardware capability, using the Internet to interlink these testbeds would allow for testing of a much wider variety of hardware systems, not necessarily collocated with a simulation. This research introduces the Distributed Internet-Enabled Simulation/Testbed Architecture (DISTA), which allows a central simulation to connect to multiple existing testbed facilities using secure internet connections. Doing so allows satellite systems to be tested before launch without the time and expense of creating custom ground-based hardware testbeds. In addition, on-orbit maneuvers can be rapidly tested by utilizing existing testbeds before executing the maneuvers. [View Full Paper]

SESSION 19: ORBIT DYNAMICS
Chair: Tom Starchville, The Aerospace Corporation

AAS 13 – 862
The Two Body Problem Elevated to the Complex Domain

Donald L. Hitzl, Retired, Systems Analysis and Simulation Department, Lockheed Palo Alto Research Laboratory, Palo Alto, California, U.S.A; **Frank Zele**, Semi-Retired, Solar and Astrophysics Laboratory, Lockheed-Martin Advanced Technology Center, Palo Alto, California , U.S.A.

In this paper, elliptical orbits of the Two-Body Problem in 2 dimensions are elevated to the Complex Domain of 4 dimensions. The two dependent variables x(t) and y(t) are elevated to $x(t, \tau) + i\,p(t, \tau)$ and $y(t, \tau) + i\,q(t, \tau)$, respectively. The time variables "t and τ" are coupled through a single parameter θ where $\tau = t \tan \theta$ and θ is to be a small angle (2° to 10°, say). Here the absolutely simplest case of the two body problem is developed, which we call the **Restricted Two Body Problem**. We start, at t = 0 at perigee. with both the Eccentric Anomaly E and true anomaly f both = 0. Following earlier work given in References 6 to 11, it is found that p and q are, automatically, second order "perturbation sensitivities" of x and y respectively. The Perturbation Derivatives are shown to give the time variable natural frequency $\omega_\eta(t, \tau)$ and the time variable damping $\zeta_D(t, \tau)$ for the x oscillation while, for the y oscillation, these values are constant at 1 and 0 respectively. [View Full Paper]

AAS 13 – 863
Trajectory Dynamics of Gas Molecules and Galaxy Formation

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

The probability distribution of the velocity of gas molecules in a closed container is described by the kinetic theory of gases. When molecules collide or impact the walls of a container, they exchange energy and momentum in accordance with Newton's laws of motion. Between collisions, the trajectory of individual molecules is a straight line, neglecting gravity. During the formation of a galaxy, the stars are constrained to a region of space and exchange energy and momentum in a manner similar to molecules. In this paper, an exact model of an ideal gas is derived and analyzed to determine the probability distribution of the molecular velocities, which are then compared with the probability distribution of velocities associated with stars during galaxy formation.
[View Full Paper]

AAS 13 – 864

Searching for Orbits That Can be Controlled by Natural Forces

Thais C. Oliveira, **Antonio F. B. A. Prado** and **Evandro M. Rocco**, Instituto Nacional de Pesquisas Espaciais (INPE), Engenharia e Tecnologia Espaciais, Mecânica Espacial e Controle, São José dos Campos, São Paulo, Brazil; **Arun K. Misra**, Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada

This paper proposes a procedure to map orbits with respect to the perturbation forces with the goal of finding orbits that may use the solar radiation pressure for station-keeping maneuvers. The calculations are made based on the measurement of the total effects of the disturbing forces obtained by using the integrals of those forces over the time. The paper shows different types of integrals of the perturbing forces over the time. These integrals represent the total change of velocity per orbit that the satellite receives from the perturbing forces. Solar radiation pressure, J2 to J4 zonal harmonics terms of the geopotential, and lunisolar perturbations are considered. The results provide the magnitude of each perturbing forces, so it is possible to see if the radiation pressure can be used to control the effect of other forces or at least to help in reducing the cost of the control. [View Full Paper]

AAS 13 – 865

Long-Term Dynamics and Stability of GEO Orbits:
The Primacy of the Laplace Plane

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

The geosynchronous Earth orbit (GEO) is in a region of space where the perturbing effects due to Earth's oblateness and lunisolar gravitational forces are comparable. On the classical Laplace plane, the secular orbital evolution driven by the combined effects of these perturbations is zero, so that the orbits are frozen. We explore the dynamics and stability of GEO orbits, and show how solar radiation pressure modifies the Laplace plane equilibrium. We discuss the implications of these results for the high area-to-mass ratio debris population, and show how the classical Laplace plane can be used as a robust long-term disposal orbit. [View Full Paper]

AAS 13 – 866
(Paper Withdrawn)

AAS 13 – 867

The Eccentric Behavior of Nearly Frozen Orbits

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Frozen orbits are orbits which have only short-period changes in their mean eccentricity and argument of periapse, so that they basically keep a fixed orientation within their plane of motion. Nearly frozen orbits are those whose eccentricity and argument of periapse have values close to those of a frozen orbit. We call them "nearly" frozen because their eccentricity vector (a vector whose polar coordinates are eccentricity and argument of periapse) will stay within a bounded distance from the frozen orbit eccentricity vector, circulating around it over time. For highly inclined orbits around the Earth, this distance is effectively constant over time. Furthermore, frozen orbit eccentricity values are low enough that these orbits are essentially eccentric (i.e., off center) circles, so that nearly frozen orbits around Earth are bounded above and below by frozen orbits.
[View Full Paper]

AAS 13 – 868
(Paper Withdrawn)

AAS 13 – 869

Approximation of Probability Density Functions Propagated Through the Perturbed Two-Body Problem

Michael Mercurio, **Reza Mandankan**, **Puneet Singla** and **Manoranjan Majji**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

This paper presents the details associated with the development of approximate probability density function (PDF) expressions for its evolution along a batch of trajectories. The exact value of the PDF is determined using the transformation of variables formula, in conjunction with the Abel's identity for the evolution of the determinant of the state transition matrix along the trajectory of the dynamical system of interest. Global Local Orthogonal MAPping (GLO-MAP) process is employed to construct the approximate PDFs from the exact values that are scattered in the phase fluid. The methodology is applied to representative dynamical systems, including the perturbed two body problem to demonstrate the effectiveness of the tools developed in this paper.
[View Full Paper]

AAS 13 – 870

Orbit Uncertainty Propagation With Separated Representations

Marc Balducci and **Brandon Jones**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.; **Alireza Doostan**, Department of Aerospace Engineering, University of Colorado, Boulder, Colorado, U.S.A.

Most approximations for stochastic differential equations with high-dimensional, non-Gaussian inputs suffer from the curse of dimensionality, thereby increasing uncertainty propagation computation costs. In astrodynamics, this results in reduced probability density function propagation accuracy. This paper considers the application of separated representations for orbit uncertainty propagation, discusses the theory behind their generation, and presents results quantifying their benefits in astrodynamics. The computation cost of a separated representation varies quadratically with dimension, thereby improving tractability. Generation of a separated representation requires the propagation of a small number of samples and yields an approximate solution to a given stochastic differential equation. This paper examines two test cases of an Earth orbiting satellite using the two body problem. In the first case, 1σ deviations in the initial conditions are relatively benign, while the second case considers larger deviations. [View Full Paper]

AAS 13 – 871

Cylindrically and Spherically Constrained Families of Non-Keplerian Orbits

Jeannette Heiligers and **Colin R. McInnes**, Advanced Space Concepts Laboratory, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, United.Kingdom

This paper introduces new families of Sun-centered non-Keplerian orbits (NKOs) that are constrained to a three-dimensional surface such as a cylinder or sphere. As such, they are an extension to the well-known families of two-dimensional NKOs. For both the cylindrical and spherical types of orbits, the equations of motion are derived in an appropriate reference frame, constraints are introduced to confine the orbit to a cylindrical or spherical surface and further constraints allow the definition of the set of feasible orbits. Additionally, the phase spaces of the orbits are explored and a numerical analysis is developed to find periodic orbits within the set of feasible orbits. The richness of the problem is further enhanced by considering both an inverse square acceleration law (mimicking solar electric propulsion) and a solar sail acceleration law to keep the spacecraft on the cylindrical or spherical surface. These new families of NKOs generate a wealth of new orbits with a range of interesting applications ranging from solar physics to astronomy and planetary observation. [View Full Paper]

SESSION 20:
ATMOSPHERIC FLIGHT AND ENTRY, DESCENT AND LANDING
Chair: Angela Bowes, NASA Langley Research Center

AAS 13 – 872

Trajectory Design Considerations for Precision Landing on Mars

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A spacecraft achieves a circular or elliptical orbit after the Mars orbit insertion maneuvers. It is demonstrated in the paper that an orbit plane adjustment or phasing maneuver plus a three-by-three targeting sequence, aiming at the longitude and latitude of the intended landing site respectively, can be used in helping achieve a precision landing on the Martian surface. It is essential to use a descent dynamic model with high fidelity and have the accurate information of the guidance law used. Also addressed is the orbit and trajectory design consideration of the tracking access conditions in planning the maneuvers. [View Full Paper]

AAS 13 – 873

Atmosphere Assessment for Mars Science Laboratory Entry, Descent and Landing Operations

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Allen Chen, **David Kass**, **Michael Mischna** and **Ashwin R. Vasavada**, Jet Propulsion Laboratory/California Institute of Technology, Pasadena, California, U.S.A.

On August 6, 2012, the Mars Science Laboratory rover, Curiosity, successfully landed on the surface of Mars. The Entry, Descent and Landing (EDL) sequence was designed using atmospheric conditions estimated from mesoscale numerical models. The models, developed by two independent organizations (Oregon State University and the Southwest Research Institute), were validated against observations at Mars from three prior years. In the weeks and days before entry, the MSL "Council of Atmospheres" (CoA), a group of atmospheric scientists and modelers, instrument experts and EDL simulation engineers, evaluated the latest Mars data from orbiting assets including the Mars Reconnaissance Orbiter's Mars Color Imager (MARCI) and Mars Climate Sounder (MCS), as well as Mars Odyssey's Thermal Emission Imaging System (THEMIS). The observations were compared to the mesoscale models developed for EDL performance simulation to determine if a spacecraft parameter update was necessary prior to entry. This paper summarizes the daily atmosphere observations and comparison to the performance simulation atmosphere models. Options to modify the atmosphere model in the simulation to compensate for atmosphere effects are also presented. Finally, a summary of the CoA decisions and recommendations to the MSL project in the days leading up to EDL is provided. [View Full Paper]

AAS 13 – 874

A Navigation Scheme for Pinpoint Mars Landing Using Radar Altimetry, a Digital Terrain Model, and a Particle Filter

Brian Gaudet and **Roberto Furfaro**, University of Arizona, Tucson, Arizona, U.S.A.

Future science-driven missions to Mars will require advanced guidance and navigation algorithms that are able to adapt to more demanding mission requirements by landing at selected locale with pinpoint accuracy while autonomously flying fuel-efficient trajectories. Current practice for navigation as applied to the powered descent phase of a Mars landing estimates the lander's downrange and crossrange position using inertial measurements and the lander's elevation using radar altimetry. As a consequence, only the lander's altitude may be accurately estimated, and downrange and crossrange position estimation errors that accumulate between the cruise stage separation and landing results in downrange and crossrange position uncertainties on the order of several kilometers. In this paper we present a novel real-time navigation algorithm that uses radar altimetry, a digital terrain model, and a particle filter to estimate the lander's position to an accuracy of several meters. We demonstrate how the navigation algorithm can be coupled with ZEM/ZEV guidance to achieve pinpoint landings on two targets unreachable using current practice: The bottom of Zumba crater and a hilltop in Uzboi Valis. [View Full Paper]

AAS 13 – 875

Neural-Based Trajectory Shaping Approach for Terminal Planetary Pinpoint Guidance

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

In this paper, we present an approach to pinpoint landing based on what we consider to be the next evolution of path shaping methodologies based on potential functions. Here, we employ Extreme Learning Machine (ELM) theories to devise a Single Layer Forward Network (SLFN) that learns the relationship between current spacecraft position and the optimal velocity field required to shape the path to the surface in a fuel efficient fashion. ELM techniques enable fast and accurate training as well as better generalization. The network is trained using open-loop, fuel-efficient trajectories that are numerically generated using pseudo-spectral methods. After test and validation, the SLFN becomes a critical element in the linear guidance algorithm loop. More specifically, a Linear Quadratic Regulator (LQR) is employed to track the optimal velocity field which is naturally defined to be attractive to the landing target. The guidance approach is tested on a simulation environment to evaluate the performance of proposed algorithm. Monte Carlo simulations show that the algorithm achieve a low guidance residual error which is less than one meter in position and less than –0.9 m/sec in impact velocity. [View Full Paper]

AAS 13 – 876

Satellite Attitude Control by Center-of-Mass Shifting

Simone Chesi and **Qi Gong**, AMS Department, U.C. Santa Cruz, Santa Cruz, California, U.S.A.; **Marcello Romano**, MAE Department, Naval Postgraduate School, Monterey, California, U.S.A.

This paper introduces a novel control technique that uses active variation of the aerodynamic torque through center of mass shifting, together with reaction wheels and magnetic torquers. The variation of the center of mass position is obtained by moving three shifting masses, which causes variation of the distances between the spacecraft's center of mass and the center of pressures of the spacecraft external surfaces. Therefore, the total aerodynamic torque acting on the satellite changes in both magnitude and direction. The main limitation of this method is related to the impossibility of generate a torque around the direction of the velocity vector. In this paper, we demonstrate how to use the shifting masses as actuators so that the aerodynamic disturbance torque can be utilized for attitude control purposes. Two control methods are introduced: one using aerodynamic torque and one reaction wheel, and the other using aerodynamic torque, and three magnetic torquers. Notably, the second method allows to compensate the well known residual oscillation error related to the use of magnetic control for spacecraft three-axes stabilization. The control authority of such system is proportional to the value of the external disturbance force acting on the satellite. For this reason, the proposed method is more efficient in an environment with high disturbance torques such as low Earth orbits. Furthermore, this method is based on adaptive nonlinear feedback control, where the system stability has been analyzed through the Lyapunov stability theory. [View Full Paper]

AAS 13 – 877

Development of a Hybrid Navigation System for the Third Sharp Edge Flight Experiment (SHEFEX-3)

Malak A. Samaan and **Stephan Theil**, DLR, German Aerospace Center, Institute of Space Systems, Bremen, Germany

The SHEFEX-2 rocket was successfully launched in June, 2012 from Andoya Rocket Range in Norway by the German Aerospace Center. The main purpose of this mission was to investigate possible new shapes for future launcher or re-entry vehicles, specifically, shapes with faceted surfaces and sharp edges. The rocket was unguided during the propelled flight phases and actively controlled during reentry with canards.

The SHEFEX-3 mission is proposed to further pursue the technology development for reentry vehicles using the extended flight experiment and shall be launched in 2016 in a suborbital trajectory.

The accurate control of the SHEFEX-3 vehicle using control flaps and moving masses requires a high-accuracy measurement of the angle of attack and the side slip angle. Both angles can only be derived from the flight path and an accurate inertial attitude measurement. The first can be achieved by using GPS measurements. The second can not be provided by an inertial navigation system due to the fact that drifts resulting from launch vibrations exceed the tolerance of the system. Therefore, a star tracker and sun sensors are utilized to update the attitude information shortly before re-entry. The presented work will describe the concept of the integrated hybrid navigation system. A special focus is also placed on the analysis of how the attitude sensors can be integrated into the SHEFEX-3 probe. [View Full Paper]

AAS 13 – 878

Modeling Satellite Drag Coefficients With Response Surfaces

Piyush M. Mehta, **Andrew Walker** and **Earl Lawrence**, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.; **Richard Linares**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.; **David Higdon** and **Josef Koller**, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

Satellite drag coefficients are a major source of uncertainty in predicting the drag force on satellites in low Earth orbit (LEO). Among other things, accurately predicting the orbit requires detailed knowledge of the satellite drag coefficient. Computational methods are important tools in computing the drag coefficient but are too intensive for real-time predictions. Therefore, analytic or empirical models that can accurately predict drag coefficients are desired. This work uses response surfaces to model drag coefficients. The response surface methodology is validated by developing a response surface model for the drag coefficient of a sphere. The response surface model performs well in predicting the drag coefficient of a sphere with a root mean square error less than 0.3% over the entire parameter space. For more complex geometries, such as the GRACE satellite, the model error is only slightly larger with an error less than 0.7%.
[View Full Paper]

AAS 13 – 879

Solution of Yaroshevskii's Planetary Entry Equation Via a Perturbative Method

Sarag J. Saikia, **James M. Longuski**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Jeffrey F. Rhoads**, School of Mechanical Engineering, Purdue University, West Lafayette, Indiana, U.S.A.

An analytical solution for ballistic entry problems at circular speed is obtained for Yaroshevskii's planetary entry equation. Using the Poincaré-Lindstedt method, explicit expressions for planar motions—velocity, altitude, flight path angle. Generalized Yaroshevskii's planetary entry equations are derived and solved for ballistic entry at circular speed for the case of zero or small initial flight path angles. The solutions are verified to be highly accurate via numerical simulation. [View Full Paper]

AAS 13 – 880

Analytical Theory for Ballistic Entry at Circular Speed for Various Flight Path Angles

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An analytical theory is developed for ballistic entry at circular speed at zero initial flight path angle and ballistic entry for very small to large initial flight path angles. Two separate solutions are needed to avoid a singularity. The theory has applications to an entry which may have an arbitrary constant ballistic coefficient. The classical Yaroshevskii's solution enters as the zero-order term in the solutions. Explicit analytical expressions for deceleration and heating are also developed. The accuracy of the solutions is verified via numerical integration of the exact equations of motion.
[View Full Paper]

AAS 13 – 881

Analytical Theory for Ballistic Entry at Moderate to Large Initial Flight Path Angles

James M. Longuski and **Sarag J. Saikia**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

Universal planetary entry equations are used to develop an analytical theory for ballistic entry for moderate to large initial flight path angles. Chapman's altitude variable is used as the independent variable. Poincaré's method of small parameters is used to develop analytical solutions for the velocity and the flight path angle. Expressions for deceleration and aerodynamic heating are also developed. The classical approximate solution of Chapman's entry equation appears as the zero order term in the new solution. The theory is very accurate for large entry angles, any entry speed and has a wide range of applications. [View Full Paper]

SESSION 21: LUNAR MISSION DESIGN AND CONCEPTS
Chair: Roby Wilson, Jet Propulsion Laboratory

AAS 13 – 882

Trajectory Design for Moonrise: A Proposed Lunar South Pole–Aitken Basin Sample Return Mission

Jeffrey S. Parker, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.;
Timothy P. McElrath, **Rodney L. Anderson** and **Theodore H. Sweetser**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

This paper presents the mission design for the proposed MoonRise New Frontiers mission: a lunar far side lander and return vehicle, with an accompanying communication satellite. Both vehicles are launched together, but fly separate low-energy transfers to the Moon. The communication satellite enters lunar orbit immediately upon arrival at the Moon, whereas the lander enters a staging orbit about the lunar Lagrange points. The lander descends and touches down on the surface 17 days after the communication satellite enters orbit. The lander remains on the surface for nearly two weeks before lifting off and returning to Earth via a low-energy return. [View Full Paper]

AAS 13 – 883
(Paper Withdrawn)

AAS 13 – 884

Calculation of an Optimal Two Impulse Earth-Moon Trajectory

John McGreevy and **Manoranjan Majji**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

In this paper, variational methods are applied to the two-impulse Earth-Moon trajectory problem. Advantages of the circular-restricted three-body problem are utilized to solve the optimal control problem for this orbital transfer. The free terminal time problem is solved by performing calculations using a fixed terminal time approach, and determining the optimal terminal time from the results of the fixed-time calculations. The effect of changing initial orbit conditions is also studied. [View Full Paper]

AAS 13 – 885

Lunar L1 Earth-Moon Propellant Depot Orbital And Transfer Options Analysis

Hsuan-chen Wan and **Benjamin F. Villac**, Department of Mechanical and Aerospace Engineering, University of California, Irvine, California, U.S.A.

One concept in support of human exploration beyond low Earth orbit consists of placing fuel depots in the region of the Earth-Moon or Earth-Moon-Sun libration points. While several studies have considered this concept on halo orbits, the full range of libration point orbits has not been considered. This study further explores the broader range of quasi-periodic orbits near the LL1 point, and their associated set of transfers from the lunar surface and low lunar orbits. [View Full Paper]

AAS 13 – 886

Far-Side Lunar Ascent Trajectory Design to Earth-Moon L2 Orbit

Ann B. Dietrich, **Jeffrey S. Parker** and **George Born**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.

Samples returned from the Lunar far-side South Pole-Aitken Basin has been deemed a high priority this decade by the National Research Council. The Orion/MoonRise mission concept involves a lander in the South Pole-Aitken Basin that would retrieve samples, and then ascend to rendezvous with the Orion capsule in a halo orbit about the Earth-Moon L2 point. This paper analyzes different ascent trajectories, varying the halo orbit insertion point and flight time, and studying the fuel costs, azimuth, and flight path angle. The results are expected to aid in the development of the mission planning for missions such as Orion and MoonRise. [View Full Paper]

AAS 13 – 887

Preliminary Design of the Phasing Strategy of a Lunar Orbit Rendezvous Mission

Zhong-Sheng Wang, **Zhanfeng Meng**, **Shan Gao** and **Decheng Liu**, China Academy of Space Technology (CAST), China Space, Haidian District, Beijing, China

The preliminary design of the phasing strategy of a lunar orbit rendezvous mission is discussed in this paper. A 4-impulse maneuver scheme is selected as the baseline design to help achieve the basic goal of the phasing stage for the chaser, and an optimal nominal phasing strategy is developed based on tracking access analysis and other considerations. Also discussed are the computation of the lunar surface ascent window and the analysis of the influence of the tracking and orbit control error on the aim point dispersion using Monte Carlo numerical simulations and analytical methods.
[View Full Paper]

SESSION 22: ATTITUDE DETERMINATION AND DYNAMICS II
Chair: Jay McMahon, University of Colorado - Boulder

AAS 13 – 888
Covariance-Matrix Adaptive Method for Approximate Time-Optimal Reorientation Maneuvers

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

The Covariance Matrix Adaptive-Evolutionary Strategy (CMA-ES) method provides a high quality estimate of the control solution for a satellite reorientation problem that includes multiple path constraints. The CMA-ES algorithm offers two significant advantages over heuristic methods such as Particle Swarm or Bacteria Foraging Optimization: it builds an approximation to the covariance matrix of the cost function, and uses that to determine a direction of maximum likelihood for the search, reducing the chance of stagnation; and it achieves second-order, quasi-Newton convergence behavior. [View Full Paper]

AAS 13 – 889
Shadow Set Considerations for Modified Rodrigues Parameter Attitude Filtering

Stephen A. O'Keefe and **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

Rigid body attitude estimation algorithms have been previously formulated using Modified Rodrigues Parameter (MRP) attitude sets. MRP attitude estimation algorithms are attractive because they have been shown to have equal accuracy to and faster initial convergence than similar quaternion based filters and they avoid the quaternion constraint problem. These algorithms make use of the fact that MRP sets are not unique. Two possible MRP sets can describe a particular orientation, and singularity avoidance can be performed by switching between the original MRP set and the alternate set, known as the shadow set. Unfortunately, the non-uniqueness of MRPs can lead to significant attitude estimation errors through improper calculation of the measurement residual. The present work examines the details required for proper implementation of a MRP attitude estimation algorithm, specifically the technical details of when and how to switch to and from the MRP shadow set when calculating the measurement residual.
[View Full Paper]

AAS 13 – 890

Iterative Model and Trajectory Refinement for Attitude and Shape Control of a Dumbbell Spacecraft

Jennifer S. Hudson, Department of Mechanical and Aerospace Engineering, Western Michigan University, Kalamazoo, Michigan, U.S.A.; **Ilya V. Kolmanovsky**, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.

An Iterative Model and Trajectory Refinement (IMTR) strategy is applied to control the orientation of an elastic dumbbell spacecraft. IMTR uses two models of a system – a high-fidelity model and a low-fidelity model – to converge on an optimized trajectory. This approach is applied to attitude and shape control of spacecraft consisting of two masses connected by an elastic link, with normal and longitudinal control inputs. Targeting problems are solved near local equilibria. [View Full Paper]

AAS 13 – 891

Sun Heading Estimation Using Underdetermined Set of Coarse Sun Sensors

Stephen A. O'Keefe and **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

A comparison of two different methods to estimate the sun direction vector using an underdetermined set of cosine-type coarse sun sensors is presented. These methods are used in conjunction with a control law to reorient a spacecraft to a power positive orientation. Coarse sun sensors are commonly used to perform coarse attitude determination and accurately point a spacecraft's solar arrays at the Sun. These sensors are attractive due to their relative inexpensiveness, small size, and reduced power consumption. This paper presents two methods for accurately solving for the sun direction vector with decreased sensor requirements, the first is a simple weighted average method and the second leverages an extended Kalman filter approach. Both methods are combined with a control law and shown through numerical simulation to be capable of reorienting the spacecraft from any initially unknown attitude to a power positive state in a matter of minutes. While the EKF provides a more accurate sun heading estimate, the weighted average approach is simpler to implement and insensitive to common coarse sun sensor output calibration errors. [View Full Paper]

AAS 13 – 892

(Paper Withdrawn)

AAS 13 – 893

Attitude Determination by Minimizing Polynomial Functions Based on Semidefinite Relaxation

Yang Tian, School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin, Heilongjiang, China; **Yang Cheng**, Department of Aerospace Engineering, Mississippi State University, Mississippi State, Mississippi, U.S.A.; **John L. Crassidis**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

Many optimal attitude determination problems can be formulated as minimization problems with polynomial objective functions and polynomial constraints. For these problems, which usually have multiple local minima, a gradient-based local search method can converge to a local minimum but cannot guarantee that the global minimum is found. Based on semidefinite relaxation, the Wahba problem, the general Wahba problem, and the GPS attitude determination problem are solved as both sum-of-squares problems and generalized problems of moments. The semidefinite relaxation based attitude solutions are shown to be identical to the globally optimal attitude solutions.
[View Full Paper]

SESSION 23:
SOLAR SAILS, TETHERS, AND LARGE SPACE STRUCTURES II
Chair: Theodore Sweetser, Jet Propulsion Laboratory

AAS 13 – 894

Vibration Suppression of Large Space Truss Structure

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Hou XinBin, China Academy of Space Technology, Beijing, China

Multi-function and high-power are the trends of modern spacecraft, of which structures have the characteristics of large size, weak stiffness and low damping, such as the large space truss structure. When these structures working on the orbit are disturbed, vibration with low frequency and high amplitude is easily stirred. Because of its low damping character, the vibration is difficult to self-attenuation, and will obstruct the normal operation of the spacecraft if there is not control. The traditional structural finite element method is usually complex and inefficient, and it even makes matters worse that the element size doesn't match with the vibration wavelength. Therefore, for the purpose of simplifying the damping configuration of large space truss structure, this article adopts the energy finite element analysis method to study the ability of dampers which absorb and dissipate vibration energy in different locations, and optimizes the configuration with the dissipation energy factor. [View Full Paper]

AAS 13 – 895
(Paper Withdrawn)

AAS 13 – 896
Applications of the Electrodynamic Tether Sling

Michael J. Mueterthies, Department of Physics, Purdue University, West Lafayette, Indiana, U.S.A.; **James M. Longuski**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Jason A. Vaughn**, Space Environments and Effects, NASA Marshall Space Flight Center, Huntsville, Alabama, U.S.A.

The electrodynamic tether sling is a novel method for propellantless spacecraft propulsion which combines a tether sling with an electrodynamic tether. The electrodynamic force allows the tether to be spun up and a payload thrown with all momentum (ultimately) coming from the rotation of the Earth. The performance of the electrodynamic tether sling is assessed for various tether parameters and various tether orbits. The mass of the tether and the time to reset between launches is calculated. The performance of the electrodynamic tether sling will be compared to conventional propellants. Under ideal conditions the electrodynamic tether sling can outperform the use of conventional rocket propulsion after fewer than ten payload throws. A list of caveats (the trouble with tethers) provides a host of challenges that must be addressed before the potential advantages of the electrodynamic tether sling can be realized. [View Full Paper]

AAS 13 – 897
Active Disturbance Rejection Control for the Attitude Stabilization of a Space Tethered Platform

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

In the tethered-assisted deployment or retrieval phases of the payload, an active disturbance rejection control method based on linear extended state observer is proposed for the attitude stabilization of a tethered platform which endures time-varying disturbance moment arising from the offset. The total disturbance is treated as an extended state which can be estimated by the observer. The control law is obtained by subtracting the extended state from an optimal control law designed on the assumption with no uncertainties. Simulation results show that the method not only estimates and compensates the disturbances, but also applicable to different kinds of disturbances. The controller meets the requirements of high stability. [View Full Paper]

AAS 13 – 898
(Paper Withdrawn)

AAS 13 – 899

Lyapunov Orbits in the Jupiter System Using Electrodynamic Tethers

Kevin Bokelmann and **Ryan P. Russell**, Aerospace and Engineering Mechanics, University of Texas, Austin, Texas, U.S.A.; **Gregory Lantoine**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Various researchers have proposed the use of electrodynamic tethers for power generation and capture from interplanetary transfers. In this paper the effect of tether forces on periodic orbits in Jupiter-satellite systems are investigated. The restricted three-body problem model is perturbed and a series of simplifications allows development of a conservative system that retains the Jacobi integral. The modified equations of motion lead to new locations of equilibrium positions as tether length is changed. Modified families of Lyapunov orbits are generated as functions of tether size and Jacobi integral, leading to new resonant-like orbits atypical of unperturbed families. Zero velocity curves and stability analyses are used to evaluate the dynamical properties of tether-modified orbits and several stable orbits are identified. [View Full Paper]

SESSION 24: SPECIAL SESSION: HIGH-PERFORMANCE AND ON-BOARD COMPUTING ARCHITECTURES
Chair: Benjamin Villac, University of California - Irvine

AAS 13 – 900
(Paper Withdrawn)

AAS 13 – 901

Parallel Computation of Multiple Space Trajectories Using GPUs and Interpolated Gravity Models

Nitin Arora, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.; **Ryan P. Russell** and **Vivek Vittaldev**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.

A variety of space mechanics applications stand to benefit from fast and accurate propagations of a large set of space objects. Examples include the space catalogue, uncertainty propagation, the conjunction problem, particle filters, and Monte Carlo sensitivity analyses. In this study, a single workstation is used to achieve both speed and accuracy for multi-object trajectory simulations. A solution methodology is presented that takes advantage of 1) new high-fidelity geopotential and third-body perturbation models that efficiently trade memory for speed and 2) a Graphics Processing Unit (GPU) based integrator to achieve parallelism across multiple objects. The two methods combined lead to multiplicative speedups, making the tool four orders in magnitude faster, in some cases, compared to the same simulation performed in serial on a single CPU. A block decomposition strategy is adopted which allows for arbitrary number of bodies to be integrated for large flight times. The performance of the tool is demonstrated for 1) a dense initial distribution with up to 1,048,576 objects and 2) an enlarged version of the space catalog with 262,144 objects. The tool takes 3 hours to simulate 262,144 objects from the enlarged space catalog, for a flight time of 7 days. For the dense initial distribution of 1,048,576 objects, the computation is faster due to favorable memory access, requiring 70 minutes for a flight time of 5 days. As an example, a Molniya reference orbit and a dense-case propagation of 262,144 objects demonstrates how uncertainty distributions can quickly become non-Gaussian, even when expressed in orbital elements. This covariance realism exercise highlights the utility of the tool for propagating full non-Gaussian uncertainty distributions. [View Full Paper]

AAS 13 – 902

GPU Accelerated Conjunction Assessment With Applications to Formation Flight and Space Debris Tracking

Abel Brown and **Jason Tichy**, a.i. solutions, Inc., Lanham, Maryland, U.S.A.;
Michael Demoret, a.i. solutions, Inc., Colorado Springs, Colorado U.S.A.;
David Rand, a.i. solutions, Inc., Lanham, Maryland, U.S.A.

The primary purpose of conjunction assessment (CA) is to prevent the collision of objects in space. Typical collision scenarios involve satellites with space debris or a formation of satellites with each other. Users performing orbit propagation and CA on very large scales must judiciously moderate force model fidelity and/or acutely limit the number of objects being modeled, often due to computational limitations. Here we investigate massively parallel orbit propagation and CA utilizing general purpose graphical processing units (GPUs) which provide orders of magnitude performance increase over similar CPU based implementations. Applications to space debris tracking and formation flight are discussed. [View Full Paper]

AAS 13 – 903

Enhanced Visualization and Autonomous Extraction of Poincaré Map Topology

Wayne R. Schlei and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Xavier M. Tricoche**, Department of Computer Science, Purdue University, West Lafayette, Indiana, U.S.A.;
Christoph Garth, Department of Computer Science, University of Kaiserslautern, Kaiserslautern, Germany

Poincaré maps supply vital descriptions of dynamical behavior in spacecraft trajectory analysis, but the puncture plot, the standard display method for maps, typically requires significant external effort to extract topology. This investigation presents adaptations of topology-based methods to compute map structures in multi-body dynamical environments. In particular, a scalar field visualization technique enhances the contrast between quasi-periodic and chaotic regimes. Also, an autonomous method is outlined to extract map topology in the planar circular restricted three-body problem. The resulting topological skeleton supplies a network of design options through the interconnectivity of orbital structures. [View Full Paper]

AAS 13 – 904

Automated Stable Region Detection

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

This paper presents an automated algorithm to extract stable regions from chaoticity maps. Using image processing algorithms to cluster the map data, the regions can be represented as discrete tree structures and can be used in optimization problems as a stability constraint function. This clustering is also used in map generation to efficiently achieve high resolution maps with less number of integrations. The region detection and representation are applied to a few stability maps. To demonstrate the map generation method, a chaoticity map near a small-body is generated. [View Full Paper]

AAS 13 – 905

A Comparison of Implicit Integration Methods for Astrodynamics

Jonathan F. C. Herman, **Brandon A. Jones**, **George H. Born** and **Jeffrey S. Parker**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado U.S.A.

This paper presents a thorough and equitable comparison of two Implicit Runge-Kutta methods, collocation via Gauss-Legendre polynomials and collocation via band-limited functions. Both have promising applications in space situational awareness, low-thrust trajectory optimization, formation flying, and planetary protection. Both of these methods have already proved to match or outperform traditional integration methods in a serial implementation, with even greater potential for improvement through parallelization, but this is the first published direct comparison between these methods. A range of cases is considered that together form a representative collection of astrodynamics problems, and extensive results are presented that allow the reader to make an informed decision as to what technique to adopt for their future applications of high performance numerical integration. [View Full Paper]

SESSION 25: SSA IV: COLLISIONS AND CONJUNCTIONS

Chair: W. Todd Cerven, The Aerospace Corporation

AAS 13 – 906

Space Traffic Management (STM)

Duane E. Bird, Bellevue, Nebraska, U.S.A.

The future is here. A couple months ago, Roger D. Launius, senior curator of space history at the National Air and Space Museum at the Smithsonian Institution, told the New York Times, "There's no question, in the next couple of years there's going to be commercial space tourism." The real question is, "Are we ready for it?" In the past 16 months, three Russian Breeze-M upper stages have failed to deliver their payloads to their proper orbits. According to United States Strategic Command's (USSTRATCOM) website, www.space-track.org, one of them has become over one hundred pieces, likely the result of the propellant causing an explosion. In 2009, an Iridium satellite and a Russian Cosmos satellite collided, creating over 2200 pieces of debris. Two years earlier, a Chinese weather satellite produced over 3300 more pieces.

This paper will discuss the current circumstances around the possible, eventual development of a US space traffic management entity to complement the growing commercial space transportation industry by providing space traffic control services to enhance safety of spaceflight. [View Full Paper]

AAS 13 – 907

BLITS: A Forensic Analysis of a Probable Collision

Roger Thompson, **Glenn E. Peterson**, **John P. McVey**, **Robert E. Markin** and **Marlon E. Sorge**, The Aerospace Corporation, El Segundo, California, U.S.A.

On January 22, 2013, the Ball Lens In The Space (BLITS) satellite experienced an unanticipated change in orbit elements. BLITS is a small spherically shaped satellite used in passive laser ranging and so has no on-board propulsion, attitude control, batteries, etc., from which an internal explosion event could originate. Therefore, its orbit elements could only be changed by an external source. This paper attempts to reconstruct the BLITS event and identify possible causes. It was found that a collision with a small-untracked particle is consistent with the observed orbit changes and breakup of the BLITS spacecraft. [View Full Paper]

AAS 13 – 908

Non-Gaussian Collision Probability

Ken Chan, Chan Aerospace Consultants, South Riding, Virginia, U.S.A.

In many applications, the probability density functions (pdfs) of the Cartesian positions of both conjuncting objects are assumed to be Gaussian. Using this model, the collision probability may be easily formulated because the pdf of their relative separation is Gaussian. However, when the pdfs of the two objects are not Gaussian, the pdf of their relative separation is not Gaussian and the simpler approach breaks down completely. Hence, a more general formulation is required. This paper discusses the formulation of the problem in accordance with the collision theory of non-Gaussian pdfs and the efficient computation of the collision probability. To do this, we derive a three-dimensional convolution integral (the product of two three-dimensional non-Gaussian pdfs) involving six spatial variables so as to obtain a three-dimensional pdf for the relative position vector. Next, we perform a three-dimensional integration over the volume swept out by a hard-body sphere in a relative motion of one object with respect to the other so as to obtain the requisite collision probability. This paper presents the generalization of an unprecedented exact analytical solution to the n-dimensional convolution integral for use in probability theory for the sum or difference of two n-dimensional vectors when their probability density functions are given as step functions. In turn, this exact solution can be used as an approximate solution when the pdfs are continuous functions. [View Full Paper]

AAS 13 – 909

(Paper Withdrawn)

AAS 13 – 910

Collision Risk Assessment and Avoidance Maneuvers – First Experience With ESA's New Tool CORAM

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I. Grande-Olalla, **N. Sanchez-Ortiz** and **J. A. Pulido**, DEIMOS Space S.L.U., Tres Cantos, Madrid, Spain

The European Space Agency's (ESA) new CORAM tool, developed by DEIMOS Space, addresses two main aspects for the implementation of an appropriate collision avoidance mechanism for identified conjunction events. The first issue regards the computation of the actual collision risk associated to an event. The second is the implementation of appropriate avoidance maneuvers considering operational constraints. The paper gives an overview of the algorithms reviewed and implemented, covering e.g. low velocity encounters, complex object shapes and various types of input data for orbital information and maneuver constraints. Next, first experience gained with the new toolset in the operational ESA environment is reported. [View Full Paper]

AAS 13 – 911

A Non-Combinatorial Approach for Efficient Conjunction Analysis

Michael Mercurio, **Puneet Singla** and **Abani Patra**, Department of Mechanical & Aerospace Engineering, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

Conjunction analysis is the study of possible collisions between objects in space, and is aimed at reducing the number of collisions between manmade objects and debris orbiting the Earth. It has been found that kd-tree based methods significantly reduce computational cost while obtaining comparable results. This research extends the applicability of the tree-based approach by accounting for non-Gaussian uncertainties, as well as correcting the probabilistic nearest-neighbor search. Employing these modifications, it is expected that the favorable computational efficiency of the tree-based approach is maintained, while extending the applicability of the proposed method.
[View Full Paper]

AAS 13 – 912

Recommended Risk Assessment Techniques and Thresholds for Launch COLA Operations

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This paper describes the second phase of a study to develop uniform launch collision avoidance and risk assessment (LCOLA) guidance and practices among the various NASA launch organizations and ranges. The first phase established the accuracy levels and covariance realism of predicted launch trajectories. This second phase used these trajectory data in a large screening experiment to examine the differences in results between general perturbations and special perturbations screenings. In addition, the trade space among probability of collision (Pc) screening threshold, required duration of the launch window, and average percent of the launch window remaining open was examined; the miss distance offset values that can be used as proxies for LCOLA screenings at different Pc values, and the difficulties that this approach presents, were explored; and the degree to which the risk posture is improved by having a LCOLA program in place, as compared to launching under a "big sky" assumption in which no conjunction prediction and mitigation are performed, was assessed. [View Full Paper]

AAS 13 – 913

Analytical Non-Linear Conjunction Assessment Via State Transition Tensors in Orbital Element Space

Kohei Fujimoto, Department of Aerospace Engineering, College of Engineering, Texas A&M University, Boulder, Colorado, U.S.A.; **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, The University of Colorado, Boulder, Colorado, U.S.A.

One common assumption in existing probabilistic conjunction assessment methods is the linear propagation of Gaussian uncertainty up to the time of closest approach. In this paper, this simplification is relaxed by propagating the uncertainty non-linearly via a special analytic solution to the Fokker-Planck equation for deterministic systems and expressing the resulting probability density function with a Gaussian mixture model. The probability of collision computed using the proposed CA technique for two objects in low Earth orbit converges upon Monte Carlo results, demonstrating both the potential accuracy and efficiency of an analytical approach. [View Full Paper]

SESSION 26: FORMATION FLYING AND RELATIVE MOTION II
Chair: Hanspeter Schaub, University of Colorado - Boulder

AAS 13 – 914
(Paper Withdrawn)

AAS 13 – 915

Development of Integrated Orbit and Attitude Hardware-In-The-Loop Simulator System for Satellite Formation Flying

Han-Earl Park, **Sang-Young Park**, **Sung-Woo Kim** and **Chandeok Park**, Astrodynamics and Control Laboratory, Department of Astronomy, Yonsei University, Seoul, Republic of Korea

The development of an integrated orbit and attitude hardware-in-the-loop simulator (HILS) system for autonomous satellite formation flying is presented here. The integrated simulator system consists of an orbit HILS based on a GPS simulator and an attitude HILS based on a 3-DOF table-top air-bearing system and performs four processes (orbit determination, orbit control, attitude determination, and attitude control) which interact with each other in the same manner as actual flight processes do. Orbit determination is conducted by a relative navigation algorithm using double-difference GPS measurements and an extended Kalman filter (EKF). Orbit control uses a sub-optimal state-dependent Riccati equation (SDRE) technique. Attitude is determined from an AHRS sensor, and a PD feedback controller is used to control the attitude HILS via three momentum wheel assemblies. An integrated HIL simulation is performed for a formation reconfiguration scenario in which a deputy satellite moves from planar motion with a 500m baseline to coplanar motion with a 1,000 m baseline. By performing the four processes adequately, a 3D RMS position accuracy of 5.428 mm is achieved for relative navigation, and the deputy satellite successfully arrives at the target reconfiguration position with an accuracy of 2.598 m. Consequently, the performance of the integrated HILS and the feasibility of the applied determination/control algorithms are demonstrated by the integrated HIL simulation. The integrated simulator system developed here thus provides a ground-based testbed for realistic orbit/attitude coupled simulations of satellite formation flying missions. It can also be used as a basis for the future development of a hardware testbed for satellite formation flying technologies.
[View Full Paper]

AAS 13 – 916
(Paper Withdrawn)

AAS 13 – 917

New Research Methodology for Earth Periodic Coverage and Regularities in Parametric Localization of Optimal Low-Earth-Orbit Satellite Constellations

Yury N. Razoumny, Cosmoexport Aerospace Research Agency, Moscow, Russian Federation

The way to solve the problem of satellite constellation design was outlined in the 1960s on recognizing the importance of satellite coverage (continuous or periodic) function allowing interpreting the operation of different types of space systems. Due to the fact that Earth periodic coverage optimization is extremely complex, for many years the solutions of this problem have been searched for among a priori fixed constellation types successfully implemented before for continuous coverage, with continuous coverage seeming to be much easier than the periodic one. In this study, it is shown that the technological advance in satellite constellation design for periodic coverage could be achieved considering it as a unique and separate problem. The new research methodology for Earth periodic coverage aiming on creating methods for optimization arbitrary constellations, alternatively to traditional approach considering narrow classes of constellations to be analyzed, is described. The unknown before regularities in Earth periodic coverage and localization of optimal low-Earth-orbit satellite constellations parameters are presented and illustrated. [View Full Paper]

AAS 13 – 918

Coordinated Control of Autonomous Vehicles in Three-Dimensional Rotating Formations

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Coordinated control of multiple autonomous spacecraft and unmanned air vehicles (UAVs) have many potential applications, including space-based interferometry, surveillance and reconnaissance missions, as well as distributed sensor networks. Many of these applications are feasible only through decentralized formations that employ cooperative control protocols. Among these, rotating formations are of significant interest for aerospace engineering applications. While various results are available for circular planar formations, few results exist for three-dimensional formations. In this paper, we focus on collective 3D motions where agents, governed by double-integrator dynamics, converge on a common plane in desired circular orbits. Specifically, we propose a decentralized, globally stabilizing control protocol with inter-agent communication described by a connected, undirected acyclic graph. Analytical closed-loop solutions are derived to show exponential convergence of the vehicles to circular orbits of prescribed radius, while Lyapunov-like stability analysis is used to show asymptotic convergence to a common plane. Finally, numerical simulations are used to validate the theoretical results. [View Full Paper]

AAS 13 – 919

Sliding Mode Control for Decentralized Spacecraft Formation Flying Using Geometric Mechanics

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

This paper presents a sliding mode control-based tracking control scheme for decentralized spacecraft formation flying via a virtual leader state trajectory. The configuration space for a spacecraft is the Lie group SE(3), which is the set of positions and orientations of the rigid spacecraft in three-dimensional Euclidean space. A virtual leader trajectory, in the form of natural attitude and translational (orbital) motion of a satellite, is generated off-line. Each spacecraft tracks a desired relative configuration with respect to the virtual leader in a decentralized and autonomous manner, to achieve the desired formation. The relative configuration between a spacecraft and the virtual leader is described in terms of exponential coordinates on SE(3). A sliding surface is defined using the exponential coordinates and velocity tracking errors. A Lyapunov analysis guarantees that the spacecraft asymptotically converge to their desired state. This tracking control scheme is combined with a collision avoidance input generated from artificial potentials for each spacecraft, which includes information of relative positions of other spacecraft within communications range. Asymptotic convergence to the desired trajectory with this combined control law is demonstrated using a Lyapunov analysis. Numerical simulations are performed to demonstrate the successful application of this tracking control scheme for a decentralized formation maneuver with collision avoidance in the presence of model uncertainty and unknown external disturbances.
[View Full Paper]

AAS 13 – 920

Optimal Collision Avoidance Maneuver for Fractionated Spacecraft Within Networked System

Ran Dai, Aerospace Engineering Department, Iowa State University, Ames, Iowa, U.S.A.

This paper examines the space debris collision avoidance problem for a collection of fractionated spacecraft modules initially connected within a networked system. The objective is to find trajectory corrections that will prevent the collision from potentially hazardous object using minimum control efforts while maintaining the communication topology of the original network. The collision avoidance problem with topology constraint is firstly formulated as a general quadratically constrained quadratic programming problem. A semidefinite relaxation method followed by a convex iterative approach is developed to search for the optimal solution with fast convergence. Simulation results for spacecraft modules avoiding tracked debris within prescribed network are provided. [View Full Paper]

AAS 13 – 921

O3B Constellation Orbit Raising and Maintenance

Sébastien Herbinière, **Joël Amalric**, **Alexandre Kaltenbach** and **Olivier Vadam**, Mission Analyst and Flight Dynamics Engineers, Thales Alenia Space, Cannes, France

O3b satellite constellation is a new MEO telecommunication mission. The paper describes the flight dynamics strategy design for the orbit raising and orbit keeping phases. The operational orbit is quasi circular and equatorial at 8069 km altitude (as defined by the difference between the semi-major axis and Earth equatorial radius). Starting from the separation orbit 240 km below, a five-maneuver strategy performs the orbit raising and phasing, while keeping a low eccentricity and correcting the inclination if required. On the operational orbit, there is an inclination equilibrium point, thus the out-of-plane control is passive. The in-plane control requires only small and infrequent tangential maneuvers. [View Full Paper]

AAS 13 – 922

(Paper Withdrawn)

AAS 13 – 923

Constrained Discrete-Time State-Dependent Riccati Equation Control for Decentralized Multi-Agent Systems

Insu Chang, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.; **Joseph Bentsman**, Department of Mechanical Science & Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.; **Sang-Young Park** and **Chandeok Park**, Department of Astronomy, Yonsei University, Seoul, Republic of Korea

The objective of this paper is to introduce the constrained discrete-time state-dependent Riccati equation (CD-SDRE) technique for decentralized multi-agent systems. First, a D-SDRE for tracking control is derived analytically. Then, the latter is utilized in formulating the distributed D-SDRE control law. The constraint problem of the D-SDRE/distributed D-SDRE is then addressed by recasting it into a model predictive control (MPC) problem. Solution of the latter is then carried out using particle swarm optimization (PSO), which facilitates estimation of the states and control inputs for the D-SDRE control law calculation. The use of decentralized CD-SDRE scheme in a networked system in the presence of constraints is then systematically demonstrated by applying this scheme to reconfiguration problems of spacecraft formation flying under constrained actuation. Simulation results demonstrate the efficacy and reliability of the proposed CD-SDRE in the decentralized control of the spacecraft formation flying.
[View Full Paper]

SESSION 27: LOW-THRUST TRAJECTORY DESIGN
Chair: Jon Sims, Jet Propulsion Laboratory

AAS 13 – 924

Robust Global Optimization of Low-Thrust, Multiple-Flyby Trajectories

Donald H. Ellison, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.; **Jacob A. Englander**, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Bruce A. Conway**, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.

There are many challenging aspects of the design of multiple flyby, low-thrust trajectories. One of the most significant, from the point of view of a numerical optimizer, can be the characteristic time scale of the dynamical system. Trajectories in a setting with a short characteristic time scale (i.e. those occurring in the vicinity of Mercury or the Jovian moons) are more challenging to optimize than those with a longer time scale (i.e. trajectories to the outer solar system) because the spacecraft must often perform many revolutions about the central body as well as several flyby maneuvers. This paper introduces modifications that can be made to a multiple flyby trajectory optimizer employing the Sims-Flanagan transcription to improve its performance on challenging problems. These improvements include full specification of the problem Jacobian sparsity pattern and analytical expressions for many of its entries as well as refinements to how the problem constraints are scaled. The improvements are then quantified by solving two challenging problems: a Jovian moon rendezvous and a notional solar electric mission to Mercury. [View Full Paper]

AAS 13 – 925

Optimization of Preliminary Low-Thrust Trajectories From GEO-Energy Orbits to Earth-Moon, L1, Lagrange Point Orbits Using Particle Swarm Optimization

Andrew J. Abraham, Department of Mechanical Engineering, Lehigh University, Bethlehem, Pennsylvania, U.S.A.; **David B. Spencer**, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.; **Terry J. Hart**, Department of Mechanical Engineering, Lehigh University, Bethlehem, Pennsylvania, U.S.A.

A technique for the preliminary global optimization of a low-thrust transfer trajectory from Earth orbit to a nominal, collinear Lagrange point orbit in the Earth-moon system is presented. The initial Earth orbit has a Jacobi energy equal to that of a geosynchronous Earth orbit (GEO-energy). Particle swarm optimization (PSO) is utilized to quickly locate the globally optimal "patch-point" where the low-thrust trajectory is terminated and the spacecraft begins to ballistically coast along the stable manifold. The results of the PSO algorithm are compared with that of a stochastic Monte Carlo algorithm. [View Full Paper]

AAS 13 – 926

Minimum-Time Low-Earth Orbit to High-Earth Orbit Low-Thrust Trajectory Optimization

Kathryn F. Schubert and **Anil V. Rao**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Forida, U.S.A.

The problem of many revolution low-thrust Earth-orbit trajectory optimization is considered. The objective is to transfer a spacecraft from a parking orbit to a desired terminal orbit in minimum time. The minimum-time orbital transfer problem is posed as a nonlinear optimal control problem, and the optimal control problem is solved using a direct transcription variable-order Gaussian quadrature collocation method. It is found that the thrust-to-mass ratio holds a power relationship to the transfer time, final mass, and final true longitude. Using these power relationships obtained through regression on the collected results, it is possible to estimate the performance of a given thrust-to-mass ratio without solving for the optimal trajectory. In addition, the key structure of the optimal orbital transfers are identified. The results presented provide insight into the structure of the optimal performance for a range of small thrust-to-mass ratios and highlight the interesting features of the optimal solutions. Finally, a discussion of the performance of the variable order Gaussian quadrature collocation method is provided.
[View Full Paper]

AAS 13 – 927
(Paper Withdrawn)

AAS 13 – 928

Preliminary Sample Return Mission Design for Asteroid (216) Kleopatra

Frank E. Laipert and **James M. Longuski**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **David A. Minton**, Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana, U.S.A.

A study is performed to design a robotic sample return mission to the asteroid (216) Kleopatra. Kleopatra is located in the asteroid belt, is an M-type asteroid, and has two moons in orbit around it. Questions about its composition, and about M-type asteroids in general, make Kleopatra a desirable target for a sample return mission. A search is conducted for low-thrust trajectories between 2020 and 2040 with a 1 km/s departure V_∞ and 20 kW solar electric propulsion system. The search covers trajectories with gravity assists from one or two bodies selected from Venus, Earth, and Mars. Regular launch opportunities are found delivering net masses of at least 1000 kg using a single gravity assist from Earth or Mars and returning to Earth in less than 10 years, with many missions returning in 6.5 to 8 years. [View Full Paper]

AAS 13 – 929

Utilizing Thrust Fourier Coefficients for Sequential Targeting in a Jupiter Orbit Trajectory

Brian O. Asimba and **Jennifer S. Hudson**, Department of Mechanical and Aerospace Engineering, Western Michigan University, Kalamazoo, Michigan, U.S.A.

The trajectory dynamics of a low-thrust spacecraft can be evaluated using averaged secular equations in a finite set of thrust Fourier coefficients. These equations are applied to targeting a sequence of orbital states. The target states are selected to represent flybys of a secondary body in orbit about a primary. The secular equations determine a low-thrust control to ensure flybys on sequential revolutions at different points along the secondary's orbital path. [View Full Paper]

AAS 13 – 930
(Paper Withdrawn)

AAS 13 – 931

Solution of Optimal Continuous Low-Thrust Transfer Using Lie Transforms

M. Sanjurjo-Rivo, Bioengineering and Aerospace Department, Universidad Carlos III de Madrid, Legans, Madrid, Spain; **D. J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **M. Lara**, and **J. Peláez**, Space Dynamics Group (SDG), Universidad Politécnica de Madrid (UPM), Madrid, Spain

This paper addresses the problem of optimal constant continuous low-thrust transfer in the context of the restricted two-body problem (R2BP). Using the Pontryagin's principle, the problem is formulated as a two point boundary value problem (TPBVP) for a Hamiltonian system. Lie transforms obtained through the Deprit method allow us to obtain the canonical mapping of the phase flow as a series in terms of the order of magnitude of the thrust applied. The reachable set of states starting from a given initial condition using optimal control policy is obtained analytically. In addition, a particular optimal transfer can be computed as the solution of a non-linear algebraic equation.
[View Full Paper]

AAS 13 – 932
(Paper Withdrawn)

AAS 13 – 933
(Paper Withdrawn)

SESSION 28: PRIMITIVE BODY MISSION DESIGN AND CONCEPTS
Chair: Roberto Furfaro, University of Arizona

AAS 13 – 934
An Archetypal Mission for Exploration and Mitigation of Potentially Hazardous Near Earth Asteroids

D. C. Hyland, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.; **H. A. Altwaijry**, Space Research Institute, Riyadh, Kingdom of Saudi Arabia; **H. Kim**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.; **N. Satak** and **S. Ge**, Experimental Center for Applied Physical Systems, College Station, Texas, U.S.A.

The Apophis Exploratory and Mitigation Platform (AEMP) concept was developed as a prototype mission to explore and potentially deflect the Near Earth Asteroid (NEA) 99942 Apophis. Deflection from a potential 2036 impact will be achieved using a gravity tractor technique, while a permanent deflection, eliminating future threats, will be imparted using a novel albedo manipulation technique. This mission would serve as an archetypal template for future missions to small NEAs and could be adapted to mitigate other Earth-crossing objects. The baseline mission profile consists of six phases: launch, rendezvous, pre-mitigation exploration, short term mitigation, long term mitigation, and post-mitigation investigation. [View Full Paper]

AAS 13 – 935
Preparatory Study: Accessing Asteroids on Horseshoe Orbits

Guillaume Rivier, Department of Aeronautics and Astronautics, University of Tokyo, Bunkyo-ku, Tokyo, Japan; **Jun'ichiro Kawaguchi**, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Jun Matsumoto**, Department of Aeronautics and Astronautics, University of Tokyo, Bunkyo-ku, Tokyo, Japan

There is a handful number of particular asteroids on "Horseshoe Orbits." Eventually, some of them would run close to L1 or L2 points, from where a spacecraft may fly along the horseshoe orbits with infinitesimally small departure/return ΔV. So, if the flight period becomes long but still admissible, those asteroids might be interesting targets for exploration or capture missions. Yet, from the synodic period point of view, they appear hardly accessible and not practical. The paper investigates a qualitative approach to reach potential targets on horseshoe orbits thanks to zero-velocity curves, and discuss the possibility of application to known objects. [View Full Paper]

AAS 13 – 936

Trajectory Design for the Exploration of Phobos and Deimos

Brent W. Barbee, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Damon Landau**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The two moons of Mars, Phobos and Deimos, are among the potential destinations for future human explorers. In this paper we present results from recent NASA working group studies in the areas of orbit analysis and trajectory design for human space flight missions to explore Phobos and Deimos. The evolution of the moons' orbits under natural perturbations are analyzed, which informs the design and optimization of trajectories to rendezvous with each moon in turn after arriving and inserting into a highly elliptical parking orbit. The abilities of the moons to support captured orbits during proximity operations are also considered. The results for optimal rendezvous trajectories between the moons, terminal rendezvous profile designs, and analysis of the Δv and time required for reorientation of a highly elliptical parking orbit at Mars, to align with incoming and outgoing asymptotes for Mars arrival and departure, are synthesized to assess the required total Δv at Mars, not including Earth departure Δv or Earth return entry speed management Δv. We find that the total Δv performed in the vicinity of Mars for human space flight missions to explore Phobos and Deimos will range between 4.5 and 10.5 km/s, depending on the mission's Earth departure date and the type of round-trip trajectory flown. [View Full Paper]

AAS 13 – 937

Optimized Free-Return Trajectories to Near-Earth Asteroids Via Lunar Flyby

Nicholas Bradley, **Sonia Hernandez** and **Ryan P. Russell**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, W.R. Woolrich Laboratories, Austin Texas, U.S.A.

An algorithm is presented to generate an initial guess and converge a trajectory to reach a near-Earth asteroid in a fuel-optimal sense with emphasis on manned-mission risk reduction. The trajectory is designed such that the departing vehicle will return to Earth with no extra maneuvers, and incorporates a lunar flyby on the outbound segment to reduce fuel cost. The nominal mission departs the free-return trajectory to rendezvous with the asteroid for a minimum period of time before returning to Earth. The optimization scheme incorporates a full ephemeris model and analytical gradients for accurate convergence. The method is useful for fuel cost reduction of interplanetary trajectories in general that include a lunar flyby. An example case is presented to rendezvous with asteroid 2000 SG344 that departs Earth on 30 March 2028 and returns from the nominal mission on 24 March 2029 for a total mission cost of 3.850 km/s and duration of 359 days. The total cost of the mission is an improvement from previous work, and is comparable to patched conic rendezvous missions that do not incorporate a free-return segment. [View Full Paper]

AAS 13 – 938

Trajectory Optimization for a Mission to the Trojan Asteroids

Shivaji S. Gadsing and **Jennifer S. Hudson**, Department of Mechanical and Aerospace Engineering, Western Michigan University, Kalamazoo, Michigan, U.S.A.

A dynamic programming algorithm is developed for the problem of finding a minimum-fuel trajectory for a mission to the Jovian Trojan asteroids. The problem is formulated as a modified traveling salesman problem. The General Mission Analysis Tool (GMAT) is employed within the direct graph algorithm for finding the optimum trajectory with minimal fuel consumption. The selection of a minimum-fuel trajectory, and the associated target asteroids, will be a key factor in determining feasibility and scientific value of a Trojan tour and rendezvous mission. [View Full Paper]

AAS 13 – 939

Following Sungrazing Comets Exploration of a Mission Concept

Adam R. Shutts and **Benjamin F. Villac**, Department of Mechanical and Aerospace Engineering, University of California, Irvine, California, U.S.A.

This paper investigates a space mission concept that consists of a spacecraft following a sungrazing comet along its orbit while consistently remaining within the shadow of the object. By locating the spacecraft within the shadow of the comet at its L2 equilibrium point, the spacecraft can be shielded from the immense radiation of the Sun. This concept provides a new vantage point to observe comet/Sun interactions while investigating the effects of outgassing and exploring the physical consequences of close perihelion passage. Shadow sizing, calculation of the L2 point, station-keeping methods, and temperature analysis are examined. [View Full Paper]

AAS 13 – 940

Solar Sail Trajectory Design for Exploration of Asteroids from/to Space Port Around L2 Point

Taku Hamasaki, Department of Aeronautics and Astronautics, University of Tokyo, Bunkyo-ku, Tokyo, Japan; **Jun'ichiro Kawaguchi**, Department of Space Flight Systems, Institute of Space and Astronautical Science, Sagamihara, Kanagawa, Japan

This paper focuses on a round-trip trajectory design for solar sailing exploration. Recently, round-trip sample return missions are gathering strong attention owing to the great achievement by Hayabusa. While, solar sailing technology is now developing, which is a technology to obtain acceleration by making use of solar radiation pressure, and is regarded as an efficient technology for the deep-space exploration. And currently there can be expected a plan of Deep Space Port around L2 point in the Sun-Earth system; it will make solar sailing exploration efficient. In this context, the objective of this study is designing and investigating the round-trip exploration trajectory originating from and ending at L2 point. The whole sequence is divided into several phases, and each of them is optimized. This trajectory design method is useful for asteroid fly-by and sample return missions. Besides, station keeping orbits around L2 point are designed. Two kinds of control are considered; attitude control and spin rate control, and both proved to be available for making the periodic orbit. Although the designed orbits are unstable, a stabilization method based on feedback control is established in this paper. Both direct control of the attitude and attitude control via only spin rate control stabilize the periodic orbit. [View Full Paper]

AAS 13 – 941

(Paper Withdrawn)

AAS 13 – 942

Detection and Characterization of Near Earth Asteroids Using Stellar Occultation

Haithem A. Altwaijry, Space Research Institute, Riyadh, Kingdom of Saudi Arabia; **David C. Hyland**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

This paper describes a technique to detect and characterize Near Earth Asteroids (NEAs), by using a formation of telescope-carrying cube-sats that observe the intensity patterns of stellar occultations. Advanced optical processing of the recorded intensity data is employed to deduce the size, shape, and albedo of detected NEAs. The technique would greatly extend conventional occultation technology to produce sharp silhouettes of NEAs even when their shadows in starlight are heavily diffracted. The work concentrates on asteroids that are small enough that only a small fraction have been detected, yet are large enough to cause significant destruction in the event of an Earth impact. [View Full Paper]

AAS 13 – 943

NEA Mitigation Via the Yarkovsky Effect

D. C. Hyland, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.; **H. A. Altwaijry**, Space Research Institute, Riyadh, Kingdom of Saudi Arabia; **H. Kim**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.; **N. Satak** and **S. Ge**, Experimental Center for Applied Physical Systems, College Station, Texas, U.S.A.

To alter the orbit of a Near Earth Asteroid (NEA) over an extended period, we propose to alter the NEA albedo to either diminish or enhance the Yarkovsky effect. At present, the albedo change mechanism that appears the most effective involves a device that dispenses charged powder onto the NEA surface – which is itself ionized by ultraviolet radiation. Electrostatic attraction provides the dominant force that attracts and binds the powder to the surface. The albedo change dispenser described here is based upon triboelectric powder dispensing technology. We describe the design details and the constraints on particle size and dispensing speed. [View Full Paper]

PLENARY SESSION

APPENDIX A

"Mambo Dogfish to the Banana Patch:" Bridging the Gap Between Technology and Policy to Unleash a Dramatic Surge in Space Capabilities (Abstract Only)

David Barnhart, Program Manager, Defense Advanced Research Projects Agency (DARPA) Tactical Technology Office (TTO), 675 North Randolph Street, Arlington, Virginia 22203-2114, U.S.A.

Democratization in technology is enabling surges in areas that benefit individual lives, society and the world in general. This same trend is beginning to occur in one medium that has eluded all but the very few well-funded organizations, that of space. Space may hold the greatest potential for expansion of markets and capabilities into the future, yet it is adjudicated by a set of policies and regulations that are typically decades old. Technology democratization in space is occurring at such a rapid pace, there may well be a clash between those policies and the true capabilities that technology may enable. The presentation will focus on understanding the natural struggle between technology advances versus possible risks they engender in the unique environment of space, and postulate ways technologists could incorporate this into every day developments to truly unleash the same surge in space currently enjoyed on Earth.

APPENDIX B
Overview of Mission Design for NASA Asteroid Redirection Mission Concept (Abstract Only)

Nathan J. Strange, Mission Concepts Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099, U.S.A.

Part of NASA's new asteroid initiative is a robotic mission to capture a roughly six to eight meter asteroid and redirect its orbit to place it in trans-lunar space. Once in a stable storage orbit at the Moon, astronauts will then visit the asteroid for science investigations, to test in space resource extraction, and to develop experience with human deep space missions. This talk will discuss the mission design techniques that enable the redirection of a 100-1000 metric ton asteroid into lunar orbit with a 40-50 kW Solar Electric Propulsion (SEP) system. The mission design is still in the early stages, and we welcome any comments from the astrodynamics community on our methodology or suggestions of alternate approaches.

Author Index