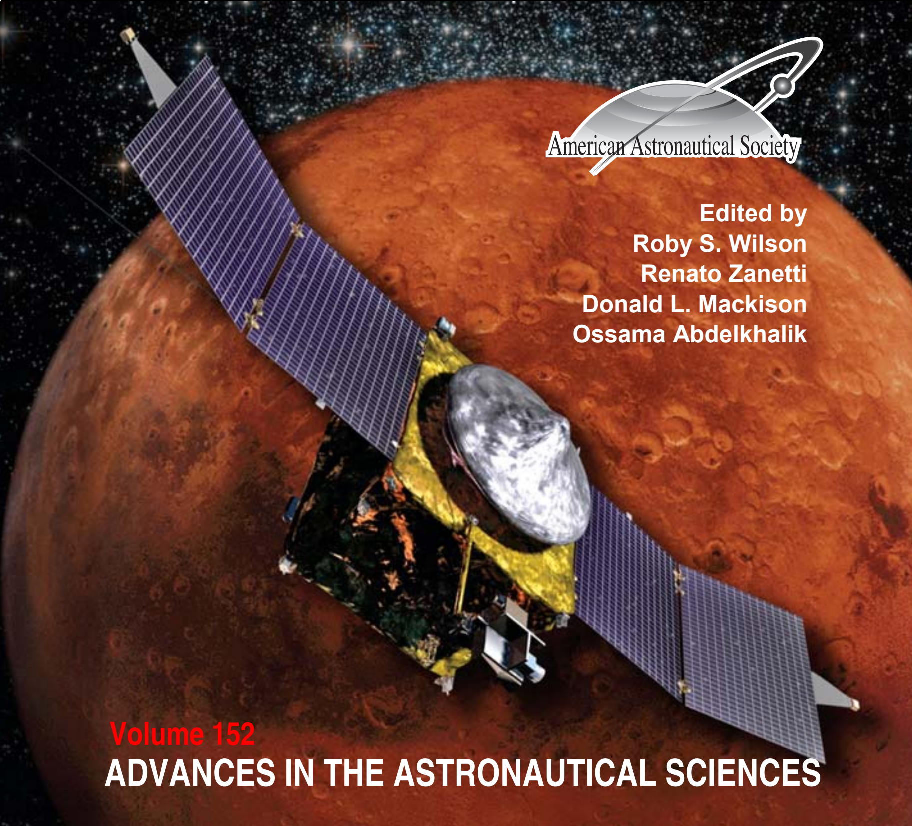
# SPACEFLIGHT MECHANICS 2014



American Astronautical Society

Edited by
Roby S. Wilson
Renato Zanetti
Donald L. Mackison
Ossama Abdelkhalik

Volume 152

ADVANCES IN THE ASTRONAUTICAL SCIENCES

# SPACEFLIGHT MECHANICS 2014

**Front Cover Illustration:**

The Mars Atmosphere and Volatile Evolution Mission (MAVEN) successfully launched on November 18, 2013. MAVEN is the first spacecraft devoted to exploring and understanding the Martian upper atmosphere. The trip to Mars takes 10 months, and MAVEN will go into orbit around Mars in September 2014. Credit: NASA Goddard Space Flight Center.

# SPACEFLIGHT MECHANICS 2014

## Volume 152

## ADVANCES IN THE ASTRONAUTICAL SCIENCES

**Edited by**
**Roby S. Wilson**
**Renato Zanetti**
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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

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

*Spaceflight Mechanics 2014*, Volume 152, Advances in the Astronautical Sciences, consists of four parts totaling about 3,800 pages, plus a CD ROM which contains all the available papers in digital format. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume. A chronological index and an author index are appended to the fourth part of the volume.

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

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

The current proceedings are valuable to keep specialists abreast of the state of the art; however, even older volumes contain some articles that have become classics and all volumes have archival value. This current material should be a boon to aerospace specialists.

## AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

**Spaceflight Mechanics 2014** appears as Volume 152, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the 24th AAS/AIAA Space Flight Mechanics Meeting 2014.

**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*).

## AAS/AIAA ASTRODYNAMICS VOLUMES

**Astrodynamics 2013**, Volume 150, Advances in the Astronautical Sciences, Eds. S.B. Broschart et al., 3532p, three parts plus a CD ROM Supplement.

**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

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**Robert H. Jacobs, Series Editor**

# PREFACE

The 2014 Space Flight Mechanics Meeting was held at the La Fonda Inn in Santa Fe, New Mexico from January 26th to 30th 2014. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Technical Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. The 232 people who registered for the meeting included 92 students, as well as professional engineers, scientists, and mathematicians representing the government, industry, and academic sectors of the United States and 13 other countries. There were 220 papers presented in 27 sessions on topics spanning the breadth of current research in astrodynamics and space flight mechanics.

Our plenary session this year was given by Moriba Jah, Michele Gaudreault, and Timothy (TK) Roberts, with special assistance from Belinda Marchand. The session detailed the Air Force Space Command (AFSPC) Astrodynamics Innovation Committee (AIC), its Astrodynamics Collaborative Environment (ACE), and the mechanism for community involvement, namely, the Air Force Research Laboratory (AFRL) Advanced Sciences and Technology Research Institute for Astronautics (ASTRIA). The session was very well attended and provided much information on what the Air Force is doing and how the broader astrodynamics community can become involved.

On Tuesday evening, the Brouwer Award Lecture was given by Dr. Robert Bishop, the 2013 AAS Dirk Brouwer Award Honoree. Dr. Bishop is the Dean of Engineering at Marquette University and holds a faculty position in the Department of Electrical and Computer Engineering. Previously he held the position of Chairman of the Department of Aerospace Engineering and Engineering Mechanics at The University of Texas at Austin where he held the Joe. J. King Professorship and was a Distinguished Teaching Professor. His lecture was entitled "A Navigator's Journey" and detailed his research and teaching, as told through the stories of the people, programs, and places stretching across time from early Space Shuttle rendezvous missions to plans for precision fast-to-flight entry, descent, and landing navigation with hazard detection and avoidance.

The editors would like extend their sincerest gratitude to each of the Session Chairs that helped make this meeting a success: Felix Hoots, Fernando Abilleira, Bob Melton, Kathleen Howell, Fu-Yuen Hsiao, Brian Page, Yanping Guo, Anastassios Petropoulos, Laureano Cangahuala, Carolin Frueh, Tom Starchville, Kohei Fujimoto, Chris Ranieri, Ryan Russell, Roberto Furfaro, Angela Bowes, Jay McMahon, Aline Zimmer, Lincoln Wood, David Finkelman, Moriba Jah, Maruthi Akella, Kyle DeMars, Jeff Parker; and double thanks to GeoffryWawrzyniak and Marcus Holzinger for chairing two sessions each. We would also like to thank the numerous volunteers who staffed the registration and information tables during the conference. Your help is much appreciated. Lastly, we would like to thank the authors for their efforts in performing world-class research and their dedication to present their

work to our astrodynamics community. We are all richer for your service and commitment to excellence.

| | |
|---|---|
| **Dr. Roby S. Wilson**<br>**Jet Propulsion Laboratory**<br>**AAS Technical Chair** | **Dr. Donald L. Mackison**<br>**University of Colorado**<br>**AAS General Chair** |
| **Dr. Renato Zanetti**<br>**NASA Johnson Space Center**<br>**AIAA Technical Chair** | **Ossama Abdelkhalik**<br>**Michigan Technological University**<br>**AIAA General Chair** |

# PAPERS BY NUMBER AND TITLE

**Volume 152 I, II, III & IV**
**ADVANCES IN THE ASTRONAUTICAL SCIENCES**
**SPACEFLIGHT MECHANICS 2013 (2013)**

(AAS/AIAA Space Flight Mechanics Meeting, January 26–30, 2014, Santa Fe, New Mexico, U.S.A.)

**SESSION 3: ASTRODYNAMICS ALGORITHMS**



**SESSION 4: LOW ENERGY TRAJECTORY DESIGN**

**SESSION 9: ORBIT DETERMINATION I**



**SESSION 10: ATTITUDE DETERMINATION AND SENSORS**

**SESSION 11: LOW-THRUST TRAJECTORY DESIGN**



**SESSION 12: ORBITAL DEBRIS**

AAS 14 – 323 Disposal Strategies for Spacecraft in Lagrangian Point Orbits, R. Armellin, P. Di Lizia, G. Di Mauro, M. Rasotto and M. Landgraf

AAS 14 – 324 Analytical Model for the Propagation of Small Debris Objects After a Fragmentation Event, Francesca Letizia, Camilla Colombo and Hugh G. Lewis

AAS 14 – 325 End-of-Life Earth Re-Entry for Highly Elliptical Orbits: The Integral Mission, Camilla Colombo, Francesca Letizia, Elisa Maria Alessi and Markus Landgraf

AAS 14 – 326 Orbital Anomaly Analysis to Detect Breakups in GEO, Masahiko Uetsuhara and Toshiya Hanada

AAS 14 – 329 Satellite Breakup Debris Cloud Characterization, Felix R. Hoots and Brian W. Hansen

**SESSION 13: SPACE SITUATIONAL AWARENESS II**

AAS 14 – 331 Collision Avoidance Maneuver Design Based on Multi-Objective Optimization, Alessandro Morselli, Roberto Armellin, Pierluigi Di Lizia and Franco Bernelli-Zazzera

AAS 14 – 334 Phylogenetic Taxonomy for Artificial Space Objects, Carolin Früh, Moriba K. Jah, E. Valdez, P. Kervin and T. Kelecy

AAS 14 – 335 Collision Avoidance Maneuver Optimization, Claudio Bombardelli, Javier Hernando Ayuso and Ricardo García Pelayo

AAS 14 – 336 Parallel Construction of Ordered Binary Radix Trees for Collision Detection, Abel Brown, Michael Demoret, Jason Tichy and Ben Schilling

AAS 14 – 339 Photometric Data From Non-Resolved Objects for Space Object Characterization, Richard Linares, Michael Shoemaker, David M. Palmer, David C. Thompson and Josef Koller

**SESSION 14: ESTIMATION**

AAS 14 – 343 Coordinatization Effects on Non-Gaussian Uncertainty for Track Initialization and Refinement, James S. McCabe and Kyle J. DeMars

AAS 14 – 344 An Automatic Domain Splitting Technique to Propagate Uncertainties in Highly Nonlinear Orbital Dynamics, Alexander Wittig, Pierluigi Di Lizia, Roberto Armellin, Franco Bernelli Zazzera, Kyoko Makino and Martin Berz

AAS 14 – 345 Adaptable Iterative and Recursive Kalman Filter Schemes, Renato Zanetti

AAS 14 – 346 Error Estimation and Control for Efficient and Reliable Orbit (and Uncertainty) Propagation, Jeffrey M. Aristoff, Joshua T. Horwood, Navraj Singh and Aubrey B. Poore

AAS 14 – 347 Orbital Density Determination From Unassociated Observations: Uninformative Prior and Initial Observation, Liam M. Healy and Christopher Binz

AAS 14 – 349 Drag Coefficient Estimation Using Satellite Attitude and Orbit Data, Christopher L. Hassa, David B. Spencer and Sven G. Bilén

AAS 14 – 351 Estimation and Prediction for an Orbital Propagation Model Using Data Assimilation, Humberto C. Godinez and Matthias Morzfeld

**SESSION 15: SMALL BODY PROXIMITY OPERATIONS**

AAS 14 – 352 Body-Fixed Orbit-Attitude Hovering at Equilibria Near an Asteroid Using Non-Canonical Hamiltonian Structure, Yue Wang and Shijie Xu

AAS 14 – 353 Solar Sailing Apophis Rendezvous Mission With Fuel-Fixed Delta-V, Xiangyuan Zeng, Jing He, Junfeng Li, Shengping Gong, Xingshan Cai and Zhiguo Zhang

AAS 14 – 354 Asteroid Proximity Navigation Using Direct Altimetry Measurements, Jay W. McMahon, Daniel J. Scheeres and Kevin Berry

AAS 14 – 355 High-Altitude Deployment of Landers to Asteroid Surfaces Using Natural Manifolds, Simon Tardivel, Daniel J. Scheeres and Patrick Michel

AAS 14 – 356 Trajectory Design About Binary Asteroids Through Coupled Three-Body Problems, Fabio Ferrari, Michèle Lavagna and Kathleen C. Howell

AAS 14 – 357 Rosetta Lander Philae Mission: Flight Dynamics Studies for Landing Site Selection on Comet Churyumov–Gerasimenko, Eric Jurado, Alejandro Blazquez, Thierry Martin, Elisabet Canalias, Romain Garmier, Thierry Ceolin, Jens Biele and Koen Geurts

AAS 14 – 359 ZEM/ZEV Sliding Guidance for Asteroid Close-Proximity Orbital Transfer and Rendezvous, Daniel R. Wibben and Roberto Furfaro

AAS 14 – 360 Orbital Evolution and Environmental Analysis Around Asteroid 2008 EV5, Pedro J. Llanos, James K. Miller and Gerald R. Hintz

AAS 14 – 361 Heliotropic Orbits at Oblate Asteroids: Balancing Solar Pressure and J2 Perturbations, Demyan Lantukh, Ryan P. Russell and Stephen Broschart

**SESSION 16: TRAJECTORY DESIGN II**

AAS 14 – 363 2016 Mars Insight Mission Design and Navigation, Fernando Abilleira, Ray Frauenholz, Ken Fujii, Mark Wallace and Tung-Han You

AAS 14 – 364 Robotic Mars Exploration Trajectories Using Hall Thrusters, Theresa D. Kowalkowski, Zachary J. Bailey, Robert E. Lock, Erick J. Sturm and Ryan C. Woolley

AAS 14 – 365 Round-Trip Solar Electric Propulsion Missions for Mars Sample Return, Zachary J. Bailey, Erick J. Sturm, Theresa D. Kowalkowski, Robert E. Lock, Ryan C. Woolley and Austin K. Nicholas

AAS 14 – 366 Preliminary Mission Design for a Crewed Earth-Mars Flyby Mission Using Solar Electric Propulsion (SEP), Stijn De Smet, Jeffrey S. Parker, Jonathan F. C. Herman and Ron Noomen

AAS 14 – 367 Spacecraft Trajectory Design With Photonic Laser Propulsion in the Two-Body Problems, Shih-Hao Liu and Fu-Yuen Hsiao

AAS 14 – 368 There and Back Again: Using Planet-Based SEP Tugs to Repeatably Aid Interplanetary Payloads, Timothy P. McElrath and John O. Elliott

AAS 14 – 369 Orbit Design and Navigation Through the End of Messenger's Extended Mission at Mercury, James V. McAdams, Christopher G. Bryan, Dawn P. Moessner, Brian R. Page, Dale R. Stanbridge and Kenneth E. Williams

**SESSION 19: SPACECRAFT DYNAMICS**



**SESSION 20: EARTH MISSIONS**

AAS 14 – 433 Rapid Repeated Solving of the Kepler Equation Using the K-Vector Technique and Optimal Lookup Tables, Stoian Borissov, Francesco de Dilectis and Daniele Mortari

AAS 14 – 434 Uncertainty Quantification for Angles-Only Initial Orbit Determination, Ryan M. Weisman and Moriba K. Jah

AAS 14 – 435 Reconstruction of Earth Flyby by the Juno Spacecraft, Paul F. Thompson, Matthew Abrahamson, Shadan Ardalan and John Bordi

**SESSION 24: AERONOMY SPECIAL SESSION**

AAS 14 – 200 Impact: Integrated Modeling of Perturbations in Atmospheres for Conjunction Tracking, Alexei Klimenko, Sean Brennan, Humberto Godinez, David Higdon, Josef Koller, Earl Lawrence, Richard Linares, David M. Palmer, Michael Shoemaker, David Thompson, Andrew Walker, Brendt Wohlberg, Moriba Jah, Eric Sutton, Thomas Kelecy, Aaron Ridley and Craig McLaughlin

AAS 14 – 330 Multi-Model Orbital Simulation Development With Python, Sean M. Brennan, Michael A. Shoemaker, Andrew C. Walker, Humberto C. Godinez and Josef Koller

AAS 14 – 341 Simultaneous Estimation of Atmospheric Density and Satellite Ballistic Coefficient Using a Genetic Algorithm, Michael A. Shoemaker, Andrew Walker and Josef Koller

AAS 14 – 436 Gas-Surface Interactions for Satellites Orbiting in the Lower Exosphere, Andrew C. Walker, Michael Shoemaker, Piyush M. Mehta and Josef Koller

AAS 14 – 437 The Intersection of Satellite Aerodynamics And Aeronomy, David Finkleman

AAS 14 – 441 Comparison of Satellite Orbit Tomography With Simultaneous Atmospheric Density and Orbit Estimation Methods, Michael A. Shoemaker, Brendt Wohlberg, Richard Linares, David M. Palmer, Alexei Klimenko, David Thompson and Josef Koller

**SESSION 26:**
**DYNAMICS AND CONTROL OF LARGE SPACE STRUCTURES AND TETHERS**

AAS 14 – 443 Tether Design Considerations for Large Thrust Debris De-Orbit Burns, Lee Jasper and Hanspeter Schaub

AAS 14 – 444 Gravitational Actions Upon a Tether in a Non-Uniform Gravity Field With Arbitrary Number of Zonal Harmonics, Hodei Urrutxua, Jesús Peláez and Martin Lara

AAS 14 – 445 Orbital Dynamics of Large Solar Power Satellites: The Geosynchronous Laplace Plane, Ian McNally, Daniel Scheeres and Gianmarco Radice

AAS 14 – 446 Discretized Input Shaping for a Large Thrust Tethered Debris Object, Lee Jasper and Hanspeter Schaub

AAS 14 – 448 Jovian Orbit Capture and Eccentricity Reduction Using Electrodynamic Tether Propulsion, Maximilian M. Schadegg, Ryan P. Russell and Gregory Lantoine

AAS 14 – 449 Long-Term Dynamics of Fast Rotating Tethers Around Planetary Satellites, Hodei Urrutxua, Jesús Peláez and Martin Lara

AAS 14 – 471 Families of Solar-Perturbed Moon-to-Moon Transfers, Gregory Lantoine and Timothy P. McElrath

AAS 14 – 472 Establishing a Network of Lunar Landers Via Low-Energy Transfers, Jeffrey S. Parker

**DIRK BROUWER AWARD LECTURE**

AAS 14 – 473 A Navigator's Journey (Abstract and Biography Only), Robert H. Bishop

**WITHDRAWN OR NOT ASSIGNED**

AAS 14 – 207, 223, 225, 240, 248, 258, 261, 264, 268, 271, 282, 284, 296, 298, 304, 308, 313, 316, 317, 327, 328, 332, 333, 337, 338, 340, 342, 348, 350, 358, 362, 384, 389, 392, 394, 402, 404, 405, 412, 416, 417, 423, 429, 438, 439, 440, 442, 447, 456, 457, 458, 462, 463, 474, 475

## SESSION 1: SPACE SITUATIONAL AWARENESS I
**Chair: Felix Hoots, The Aerospace Corporation**

### AAS 14 – 201
**A Boundary Value Problem Approach to Too-Short Arc Optical Track Association**

**K. Fujimoto** and **K. T. Alfriend**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.; **T. Schildknecht**, Astronomical Institute, University of Bern, Bern, Switzerland

Given a short-arc optical observation with estimated angle-rates, the admissible region is a compact region in the range / range-rate space defined such that all likely and relevant orbits are contained within it. An alternative boundary value problem formulation has recently been proposed where range / range hypotheses are generated with two angle measurements from two tracks as input. In this paper, angle-rate information is reintroduced as a means to eliminate hypotheses by bounding their constants of motion before a more computationally costly Lambert solver or differential correction algorithm is run. [View Full Paper]

### AAS 14 – 202
**Distant Periodic Orbits for Space-Based Near Earth Objects Detection**

**Michele Stramacchia**, Computational Engineering and Design, University of Southampton, United Kingdom; **Camilla Colombo** and **Franco Bernelli-Zazzera**, Department of Aerospace Science and Technology, Politecnico di Milano, Milano, Italy

This article proposes a concept for the detection of Potentially Hazardous Aster-oids (PHAs) from a space-based network of telescopes placed on retrograde distant periodic orbits. Planar periodic orbits in the circular restricted three-body problem are designed, starting from initial conditions in the Hill problem available from the literature. Based on an analysis of the distance they reach from Earth, the family of retrograde orbits centered at the Earth are selected. Indeed, due to the large distance they reach from Earth, larger than the Earth-L2 distance, spacecraft on such orbits can detect PHAs incoming from the Sun direction, which could not otherwise be monitored from current Earth-based systems. A trade-off on the orbit amplitude and the number of spacecraft in the constellation is performed considering current visible sensor telescope technology. The case of Chelyabinsk meteor is proposed as real scenario.
[View Full Paper]

**AAS 14 – 203**

**Estimation for Satellite Collision Probabilities Using Importance Sampling**

**Earl Lawrence**, **David Higdon**, **Andrew Walker** and **Michael Shoemaker**, Los Alamos National Laboratory, Los Alamos New Mexico, U.S.A.

Accurate estimates for satellite collision probabilities should have three important features. First, they should include of sources of uncertainty beyond the satellite state such as environmental variables like atmospheric density and drag. Second, they should account for non-Gaussian distributions at close approach. Finally, these probability estimates need to have reasonable computational requirements so that predictions can be made in a timely manner. Although state vectors based on direct observation may follow a Gaussian distribution, this may not be true after forward propagation, particularly when environmental variables are also uncertain. The probability of collision between two satellites can, in principle, be computed via direct Monte Carlo. Unfortunately, this is impractical due to the computational demands of accurate satellite propagation and atmospheric simulation. This paper suggests an approach based on importance sampling in which a biased sample is drawn that produces more collisions than expected. The sample is then weighted to give the correct prediction. This approach allows for non-Gaussian behavior, incorporates environmental and other variables, and has reasonable computational requirements.

The suggested importance sampling approach for collisions has two stages. The first stage takes a standard Monte Carlo sample from all of the variables of interest and propagates to closest approach. We then construct a regression model that predicts miss distance based on starting conditions. We can invert this model to find regions in the space of initial conditions that produce very close passes and collisions. The second stage draws a biased sample in and around these regions and propagates them forward. The probability of collision is computed using this biased sample. This method learns an importance sampling distribution for each event of interest. The combined sample size of the two stages is smaller than the sample required for a straightforward Monte Carlo estimate with similar variance. Thus, we retain the advantages of Monte Carlo sampling at much reduced computational cost. [View Full Paper]

**AAS 14 – 204**

**Initial Orbit Determination, Data Association, and Admissible Regions of Space Objects Using Magnetometers**

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

Magnetometer-based detection and characterization of space objects is motivated and challenges are discussed. Observable constants of motion with and without charge screening are derived in detail. Batch filtering methods are proposed to estimate the observable space object states. A novel application of orbit and detection constraints is used to generate admissible region boundaries for unobservable states, allowing initial orbit determination and data association of space objects passing near magnetometers. Practical and operational issues are discussed, followed by suggested future research activities. [View Full Paper]

**AAS 14 – 205**

**"Inverse Crime" and Model Integrity in Unresolved Space Object Identification**

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

This work investigates the selection of models when producing synthetic light curves for the purpose of estimating the shape and size of unresolved space objects. Moreover, the "inverse crime" (using the same model for the generation of synthetic data and data inversion), is investigated. This is done by using two models to produce the synthetic light curve and later invert it. It is shown here that the choice of model indeed affects the estimation of the shape/size parameters. When a higher fidelity model is used to both create and invert the light curve model the estimates of the shape/size parameters are significantly better than those obtained when a lower fidelity model is implemented for the estimation. It is therefore of utmost importance to consider the choice of models when producing synthetic data, which later will be inverted, as the results might be misleadingly optimistic. [View Full Paper]

**AAS 14 – 206**

**Enabling the Use of Rotating Platforms for Orbit Determination Applications**

**Brad Sease**, Aerospace & Ocean Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.; **William Anthony**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.; **Brien Flewelling**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

Current methods for retrieving visual, space-based observations for the purpose of orbit determination are generally restricted to either sidereal-stare observations or optical tracking based on a priori knowledge. To expand the range of operating modes, an alternative method is proposed to allow data collection from rotating platforms with limited a priori knowledge of a specific target. Here we will demonstrate a novel algorithm to identify non-star objects based on apparent motion detectable in a rotating frame. With a series of correlated measurements, we also show that it is possible to extend this method for automated orbit estimation. [View Full Paper]

**AAS 14 – 207**
**(Paper Withdrawn)**

**AAS 14 – 208**

**Collision Avoidance in Elliptical Formation Flying Based on Relative Orbit Elements**

**Jianfeng Yin**, China Academy of Space Technology (CAST), Fengtai District, Beijing, China; **Yinrui Rao**, School of Astronautics, Beihang University, HaiDian District, Beijing, China; **Guo Zhong**, School of Aeronautics Science and Engineering, Beihang University, HaiDian District, Beijing, China; **Chao Han**, School of Astronautics, Beihang University, HaiDian District, Beijing, China

In this article, a new collision avoidance model is developed based on relative orbit elements. The propagation of the uncertainty estimate is studied using the unscented transform (UT) method to remove the nonlinearities. The propagation equations of the covariance matrix are derived. The collision probability model is established with the consideration of J2 perturbation. The role of the relative orbit elements is highlighted on configuration design and collision analysis. Finally the proposed methods are validated by simulation through several typical examples. [View Full Paper]

**AAS 14 – 209**

**Stochastic Optimization For Sensor Allocation Using AEGIS-FISST**

**I. I. Hussein**, Applied Defense Solutions, Columbia, Maryland, U.S.A.; **Z. Sunberg** and **S. Chakravorty**, Texas A&M University, College Station, Texas, U.S.A.; **M. K. Jah** and **R. S. Erwin**, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

In Space Situational Awareness (SSA) not only is it desired to maintain the two line elements of objects that have already been detected, but it is also desired to maintain the catalogue by updating it whenever new objects are detected for the first time. Hence, one of the main goals of SSA is to search for and detect new objects. The main challenge to achieving this goal is the fact that the sensor resources available in the SSA system are very limited compared to the very large size of the search space and number of objects (that number is in the hundreds of thousands of objects that are one centimeter and larger in size). This search and detection task needs to be performed using sensors that are often the same ones used for maintaining the tracks of detected objects. Thus, in this paper our goal is to develop a multi-object information-based objective function for sensor allocation. However, conventional information-based approaches to the sensor allocation problem are mostly dedicated to the problem of sensor allocation for multi-object tracking (without detection). Thus, we develop a Finite Set Statistical (FISST) approach to sensor allocation for joint search, detection and tracking. We demonstrate the procedure on a simple two-object SSA problem. The resulting information objective function will then be used to optimally task the sensor. The resulting optimization problem is computationally intractable. Therefore, we use a stochastic optimization technique that was developed by the authors to solve for the optimal sensor tasking. [View Full Paper]

### AAS 14 – 210

**Particle Filtering Light Curve Based Attitude Estimation for Non-Resolved Space Objects**

**Richard Linares**, Space Science and Applications, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.; **John L. Crassidis**, Department of Mechanical and Aerospace Engineering, University at Buffalo, The State University of New York, Buffalo, New York, U.S.A.; **Moriba K. Jah**, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

This paper discusses the development of a particle filter for attitude and angular rate estimation of a space object using light curve observations. The particle filter approach used is based on the generalized Rodrigues parameters (GRPs) local error representation. The global state used is the quaternion to avoid singularity in the attitude states. Uniform quaternions are generated to approximate a uniform distribution of rotation states. The approach is tested with simulation scenarios and evaluated based error performance and converge rate. [View Full Paper]

## SESSION 2: RENDEZVOUS AND PROXIMITY OPERATIONS I
**Chair: Fernando Abilleira, Jet Propulsion Laboratory**

### AAS 14 – 211

**Relative Orbital Motion and Angles-Only Relative State Observability in Cylindrical Coordinates**

**David K. Geller**, Mechanical and Aerospace Engineering Department, Utah State University, Logan, Utah, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

The relative orbital equations of motion in cylindrical coordinates are rigorously derived in several forms included the exact nonlinear two-body differential equations of motion, the linear-time-varying differential equations of motion for an elliptical orbit chief, and the linear-time-invariant differential equations of motion for a circular orbit chief. The linear-time-invariant equations of relative orbital motion in cylindrical coordinates are found to be very similar to the corresponding equations in Cartesian coordinates (i.e., the standard Hill-Clohessy-Wiltshire equations). However, after developing the angles-only measurement equation in cylindrical coordinates, evidence of full-relative-state observability is found, contrary to the range observability problem exhibited in Cartesian coordinates. It is found that orbit curvature and elements of the relative dynamics are not sufficiently retained in the linearized Cartesian coordinate formulation, and this leads to the range observability problem. In the linearized cylindrical coordinate formulation, sufficient orbit curvature and relative dynamics are maintained and full-relative-state observability is evident. [View Full Paper]

## AAS 14 – 212

**Initial Relative Orbit Determination Performance Analysis in Cylindrical Coordinates Using Angles-Only Measurements**

**David K. Geller**, Mechanical and Aerospace Engineering Department, Utah State University, Logan, Utah, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

The solution of the initial relative orbit determination problem using angles-only measurements is important for orbital proximity operations, satellite inspection and servicing, and the identification of unknown space objects in similar orbits. In this paper, a preliminary relative orbit determination performance analysis is conducted utilizing the linearized relative orbit equations of motion in cylindrical coordinates. A geometric approach to the problem equivalent to computing the Cramer-Rao lower bound is used to estimate the expected performance of an initial relative orbit determination algorithm. To facilitate a better understanding of the problem, this paper focuses only on the 2-dimensional initial orbit determination problem. The results clearly show the dependence of the orbit estimation performance on the geometry of the relative orbit and on the time interval between observations. Analysis is conducted for leader/follower orbits where the chief and the deputy are in the same circular orbit, and flyby orbits where the deputy passes directly above or below the chief. [View Full Paper]

## AAS 14 – 213

**A Non-Singular Keplerian Differential State Transition Matrix**

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

The Keplerian differential state transition matrix (KDSTM) is a basic and fundamental tool in investigations of the sensitivity of orbital evolution to changes in initial conditions, in perturbation analysis, as well as in targeting and rendezvous operations. The "differential" attribute is used here to remark on the fact that this is not the state transition matrix of Keplerian motion, which embodies the Kepler flow, but rather the first-order mapping tool used in propagating initial state variations. Several different forms of the KDSTM are available in the literature. They differ in the choice of state space variables, as well as in derivation methods. The choice of state variables is a critical issue, since it may lead to representation singularities for some orbit types. We present here a new method for constructing the differential KSTM based on a well-known, but seldom used, theorem from the theory of ordinary differential equations related to sensitivity to initial conditions. This theorem states that the solution to the equations of variation is a linear combination of the partial derivatives with respect to the initial conditions of the solution of the nonlinear problem which generated the variational equations. An early application of this method goes back to Otto Dziobek, who used it in his book *Mathematical Theories of Planetary Motions* at the end of the nineteenth century. The power of the method in connection with the KDSTM was already indicated by Roger Broucke, who developed a similar approach to that proposed here, but only in two dimensions. Here we provide a full three-dimensional KSTM, based on Keplerian elements, but devoid of any singularity. This has been obtained by remapping the partial derivatives of the Keplerian solution in such a way as to avoid any two of them to be proportional for the special case of circular motion and to extend their validity to zero inclination. A peculiarity of the method is that it allows the construction of analytical expressions for both the direct and the inverse matrices needed to form the KDSTM. The KDSTM is first built in the inertial reference frame and then transformed to the orbital frame, which is identified by the radial, the transverse, and the normal directions at the position of the reference orbit. The method used to derive this form of the KDSTM is readily extensible to include perturbations to Keplerian motion, and indications will be given as to the inclusion of the secular pertuabations due to the oblateness of the primary. [View Full Paper]

## AAS 14 – 214

### Formation Flying and Relative Dynamics Under the Circular Restricted Three-Body Problem Formulation

**Fabio Ferrari** and **Michèle Lavagna**, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy

Formation Flying can greatly answer some very complex mission goals at the cost of a quite challenging trajectory design and station keeping problem solving. For this reason formation flying is now one of the most frequently employed architecture for space missions and relative position and velocity requirements are becoming very important in the design process. The dynamical properties of a low-acceleration environment such as the vicinity of libration points associated to the Circular Restricted Three-Body Problem (CR3BP), can be effectively exploited to design spacecraft configurations able of satisfy relative position and velocity requirements. This work analyzes the effects of the three-body dynamics on a free uncontrolled formation of spacecraft. The three-body dynamical environment is then analyzed when some constraints are imposed to the relative dynamics of two co-operating spacecraft with the perspective of providing a useful and powerful tool to support refined mission analysis for future challenging missions to be designed. [View Full Paper]

## AAS 14 – 215

### Relative Dynamics and Control of High Area-to-Mass Ratio Spacecraft Flying Around an Oblate Earth Exploiting Solar Radiation Pressure

**G. Mingotti** and **C. McInnes**, Advanced Space Concepts Laboratory, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, United Kingdom

Reconfiguration maneuvers and maintenance strategies for formation-flying are investigated in this paper, where micro-spacecraft with high area-to-mass ratio and small length-scale are considered. Assuming the exact $J_2$ nonlinear relative dynamics, an optimal control problem is formulated to accomplish the maneuvers. A continuous control acceleration is applied to the system dynamics via a propellant-free approach, which exploits differential solar radiation pressure by means of electrochromic coating. Thanks to the advances in miniaturised technology, a great number of electromechanical devices can be manufactured and deployed at low cost with active sensors on-board. A new class of space missions is enabled, based on swarms of micro-spacecraft with sensing, computing, bi-directional communicating and micro-power sources.
[View Full Paper]

### AAS 14 – 216

**Inverse Transformation of Relative State Transition Matrix Based on Relative Orbit Elements**

**Jianfeng Yin**, China Academy of Space Technology (CAST), Fengtai District, Beijing, China; **Yinrui Rao** and **Chao Han**, School of Astronautics, Beihang University, HaiDian District, Beijing, China

A new set of relative orbit elements (ROEs) is used to derive a new elliptical formation flying model in previous work. In-plane and out-of-plane relative motions can be completely decoupled, which benefits elliptical formation design. In order to study the elliptical control strategy and perturbation effects, it is necessary to derive the inverse transformation of the state transition matrix based on relative orbit elements. Poisson bracket theory is used to obtain the linear transformations between the two representations: the relative orbit elements and the geocentric orbital frame. In this paper, the details of these transformations are presented. [View Full Paper]

### AAS 14 – 217

**Relative Position Control of a Two-Satellite Formation Using the SDRE Control Method**

**Mohammad Mehdi Gomroki** and **Ozan Tekinalp**, Department of Aerospace Engineering, Middle East Technical University, Ankara, Turkey

The relative position and formation attitude control of a two-spacecraft utilizing coulomb forces as well as thrusters is addressed. The nonlinear control is realized through state dependent Riccati equation (SDRE) control method. To this end the equations of motion of the formation is properly manipulated to obtain a suitable form for SDRE control. The state-dependent coefficient (SDC) form is then formulated to include the non-linearities in the relative dynamics. The effectiveness of the controllers is demonstrated through simulations. [View Full Paper]

### AAS 14 – 218

**Use of Cartesian-Coordinate Calibration for Satellite Relative-Motion Control**

**Andrew J. Sinclair**, Aerospace Engineering Department, Auburn University, 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.

The Cartesian state of the motion of a deputy satellite relative to a chief satellite can be propagated with either nonlinear or linearized dynamics. Linearized propagation of a calibrated Cartesian state has been observed to reduce linearization error compared to linearized propagation of the true Cartesian state. Control laws are often designed assuming linearized dynamics. Implementing these controllers in the presence of the nonlinear dynamics can lead to reduced performance. However, feedback of the calibrated state can provide improved performance and reduced fuel consumption compared to feedback of the true state. [View Full Paper]

### AAS 14 – 219

**Periodic Orbits in the Elliptical Relative Motion Problem With Space Surveillance Applications**

**Ashley D. Biria** and **Ryan P. Russell**, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Texas, U.S.A.

Periodic orbits with respect to an object in an eccentric Keplerian reference orbit can be found in a variety of ways, including the use of Tschauner-Hempel equations and orbital element differences, which both admit linearized solutions, as well as through direct analyses of two orbits. An alternative parameterization of the last approach is proposed in the current study, utilizing an inertial frame and simple geometrical constructs inherent to the relative motion problem. In this manner, an intuitive and straightforward characterization of periodic orbits is established that retains the nonlinear dynamics. The resulting multi-dimensional space that defines the periodic orbits is surveyed and direct comparisons are made with the Tschauner-Hempel solutions to assess the linear region of validity. Applications focus on resident space object (RSO) surveillance and circumnavigation orbits. An orbit's effectiveness is analyzed in terms of object coverage using coverage figures of merit, including a concept introduced in this paper called "RSO tracks," the analogy of ground tracks on the body-fixed surface of an RSO. [View Full Paper]

### AAS 14 – 220

**Further Exploration of Lamberts' Problem Using Relative Satellite Dynamics**

**William Anthony**, Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona, U.S.A.; **Thomas Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

This paper represents a follow-on to previous work that investigated the Lambert problem, a well known spacecraft targeting problem, as a rendezvous problem, whereby a deputy satellite is to rendezvous with a fictitious chief. Two Lambert-like guidance algorithms based on relative motion models (one being the linear Hills-Clohessy-Wiltshire model, and the other a recent second-order closed-form solution) were presented and compared for accuracy. In this paper, the nature of the second-order algorithm is further explored, in terms of its multiple-root nature and limitations on its use. [View Full Paper]

## AAS 14 – 221

### Finite-Time Control for Body-Fixed Hovering of Rigid Spacecraft Over an Asteroid

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

A finite-time control scheme for autonomous body-fixed hovering of a rigid spacecraft over a tumbling asteroid is presented in the framework of geometric mechanics. This control scheme guarantees convergence of configuration (pose) and velocity tracking errors in finite-time with (Hölder) continuous feedback. 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's trajectory is assumed to be available through the spacecraft's on-board navigation. The relative configuration between the spacecraft and the asteroid is described in terms of exponential coordinates on the Lie group SE(3). With this feedback control, the spacecraft achieves a desired relative configuration with respect to the asteroid autonomously and in finite time, without requiring explicit reference states. Finite-time convergence of the proposed control scheme for the closed-loop system is theoretically proved using Lyapunov stability analysis. A numerical simulation demonstrates successful application of this finite-time control scheme for coupled translational and rotational maneuvers about a selected tumbling asteroid, leading to asteroid body-fixed hovering. The asymptotic tracking control was also implemented to compare with the performance of the finite-time control. [View Full Paper]

## SESSION 3: ASTRODYNAMICS ALGORITHMS
**Chair: Robert Melton, Pennsylvania State University**

### AAS 14 – 222
**Framework for Performance Comparison of Lambert Algorithms**

**Jaemyung Ahn**, **Sang-Il Lee** and **Jun Bang**, Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea

This paper proposes a framework to compare the performances of different Lambert algorithms in a systematic way. Minimal parameters that can uniquely determine the iterator of each algorithm are identified then the cost to execute a single iteration of the algorithm is calculated. A set of parameters to create experimental problem instances which can determine a unique set of input parameters for each algorithm is selected. Numerical experiments are conducted using the determined set and provide the numbers of iterations for solved problem instances. The experimental results, combined with the cost per iteration, can be used to create the performance dominance map for considered algorithms. Results of a case study for performance comparison of two popular Lambert algorithms are presented to demonstrate the effectiveness of the proposed framework. [View Full Paper]

### AAS 14 – 223
**(Paper Withdrawn)**

### AAS 14 – 224
**Long-Term Orbital Propagation Through Differential Algebra Transfer Maps and Averaging Semi-Analytical Approaches**

**Alexander Wittig**, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy; **Roberto Armellin**, School of Engineering Sciences, University of Southampton, Southampton, UK; **Camilla Colombo** and **Pierluigi Di Lizia**, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy

Orbit perturbations are fundamental when analyzing the long-term evolution and stability of natural or artificial satellites. We propose the computation of transfer maps for repetitive dynamical systems as a novel approach to study the long-term evolution of satellite and space debris motion. We provide two examples of this technique, the evolution of high area-to-mass ratio spacecraft under solar radiation pressure and $J_2$, and a sun-synchronous groundtrack repeating orbit with drag and $J_2$. The results presented demonstrate the potentiality of the transfer maps for these problems. We furthermore compare this approach with averaging methods for the propagation of the orbital dynamics on the long-term, and suggest possibilities to combine differential algebra based methods with orbital elements averaging. [View Full Paper]

### AAS 14 – 225
**(Paper Withdrawn)**

## AAS 14 – 226

### Asymptotic Solution for the Two Body Problem With Radial Perturbing Acceleration

**Juan L. Gonzalo** and **Claudio Bombardelli**, Space Dynamics Group, School of Aeronautical Engineering, Technical University of Madrid (UPM), Spain.

In this article, an approximate analytical solution for the two body problem perturbed by a radial, low acceleration is obtained, using a regularized formulation of the orbital motion and the method of multiple scales. The results reveal that the physics of the problem evolve in two fundamental scales of the true anomaly. The first one drives the oscillations of the orbital parameters along each orbit. The second one is responsible of the long-term variations in the amplitude and mean values of these oscillations. A good agreement is found with high precision numerical solutions. [View Full Paper]

## AAS 14 – 227

### EDromo: An Accurate Propagator for Elliptical Orbits in the Perturbed Two-Body Problem

**Giulio Baù**, Department of Mathematics, Celestial Mechanics Group, University of Pisa, Italy; **Hodei Urrutxua** and **Jesús Peláez**, Department of Applied Physics to the Aeronautical and Space Engineering, E.T.S.I. Aeronáuticos, Space Dynamics Group, Universidad Politécnica de Madrid, Madrid, Spain

EDromo is a special perturbation method for the propagation of elliptical orbits in the perturbed two-body problem. The state vector consists of a time-element and seven spatial elements, and the independent variable is a generalized eccentric anomaly introduced through a Sundman time transformation. The key role in the derivation of the method is played by an *intermediate* reference frame which enjoys the property of remaining fixed in space as long as perturbations are absent. Three elements of EDromo characterize the dynamics in the *orbital* frame and its orientation with respect to the intermediate frame, and the Euler parameters associated to the intermediate frame represent the other four spatial elements. The performance of EDromo has been analyzed by considering some typical problems in astrodynamics. In almost all our tests the method is the best among other popular formulations based on elements. [View Full Paper]

## AAS 14 – 228

### Efficient Solutions of Kepler's Equation Via Hybrid and Digital Approaches

**Daniel L. Oltrogge**, Analytical Graphics Inc., Colorado Springs, Colorado, U.S.A.

The solution of Kepler's equation is accomplished via families of hybrid and digital techniques. The hybrid approaches couple a power series expansion starting approximation with nine different types of higher-order corrective step methods. The resulting computationally efficient non-iterative methods avoid "if" statements and directly yield in-plane Euler rotation angles necessary to map orbit elements to orbital position. The best-performing of the nine hybrid methods are up to two times faster than the original efficient Laguerre iterative method and achieve worst-case resultant true anomaly accuracies down to machine precision at $3\times10^{-11}$ ° for eccentricities up to 0.999999. This matches or exceeds the performance of iterative methods and translates to less than three micro-meters at GEO altitude. Meanwhile, six digital approaches were explored, with the best digital approach boasting a ten-fold speed increase with a worst-case accuracy of $1\times10^{-6}$ ° (154 millimeters) for an eccentricity of 0.999999. These combinations of accuracy and speed performance make both the hybrid and digital approaches well-suited for in-line incorporation into a wide range of low- to high-fidelity semi-analytic orbit propagators and multi-threaded or vector programming languages and computing hardware (GPUs, etc.). [View Full Paper]

## AAS 14 – 229

### Solutions of Multivariate Polynomial Systems Using Macaulay Resultant Expressions

**Keith A. LeGrand**, **Kyle J. DeMars** and **Jacob E. Darling**, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla Missouri, U.S.A.

Finding zeros of algebraic sets is a fundamental problem in aerospace engineering computation. Geometrically, this problem can often be represented by the intersection of multiple conic or quadric surfaces. A common example is GPS trilateration, which is geometrically given by the intersection of three spheres. In this work, Macaulay resultant expressions are used to compute the solutions of a set of multivariate polynomial expressions. Both two- and three-dimensional algebraic sets are considered, and examples of two geometric systems and their solutions are provided. [View Full Paper]

## AAS 14 – 230

**Application of the Stark Problem to Space Trajectories With Time-Varying Perturbations**

**Noble Hatten** 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.

Three methods of obtaining solutions to the Stark problem – one using Jacobi elliptic and related functions, one using Weierstrass elliptic and related functions, and one using $F$ and $G$ Taylor series extended to the Stark problem – are compared qualitatively and quantitatively. In the current implementations, the Jacobi formulation is found to be more computationally efficient than the Weierstrass formulation, while the series formulation provides the most efficiency if the order is not excessively high. The effectiveness of the Stark model in approximating space trajectories with continuously time-varying perturbations is compared to the ubiquitous Sims-Flanagan model. A method based on Adams-Bashforth numerical integration formulae is applied to the determination of disturbing acceleration vectors for each model. The method uses disturbing acceleration information from previous propagation steps to calculate a higher-order approximation of the effects of the perturbation between two steps. The increase in computation time compared to a first-order approximation is minimal because no additional propagations are required. Results for two example low-Earth orbits perturbed by $J_2$ and atmospheric drag, respectively, are presented. [View Full Paper]

## AAS 14 – 231

**Applications of Implicit Functions to Orbital Mechanics Problems**

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

Bézier curves are implicit functions which can describe complicated curves and surfaces. In most of orbital mechanics problems, conic sections are mainly interested. Using the Bézier curves, useful expressions for the orbital mechanics problems are derived. Then, two application examples are considered: (1) Kepler's equation and (2) two point boundary value problems. Analytical approach is performed and arranged in this work and it can be used for potential application in astrodynamics. [View Full Paper]

### AAS 14 – 232

**Multi-Segment Adaptive Modified Chebyshev Picard Iteration Method**

**Donghoon Kim**, **John L. Junkins** and **James D. Turner**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.;
**Ahmad Bani-Younes**, Department of Aerospace Engineering, Khalifa University, Abu Dhabi, UAE

A modified Chebyshev Picard iteration method is proposed for solving orbit propagation initial value problems. Cosine sampling, known as Chebyshev-Gauss-Labatto (CGL) node, is used to reduce the Runge's phenomenon that plagues many series approximations. The key benefit of using the CGL data sampling is that the nodal points are distributed non-uniformly, with dense sampling at the beginning and end times. This problem can be addressed by a nonlinear time transformation and/or by utilizing multiple time segments over an orbit. This paper suggests a method, called a multi-segment method, to obtain accurate solutions overall regardless of initial positions and eccentricity by dividing the given orbit into two or more segments. [View Full Paper]

## SESSION 4: LOW ENERGY TRAJECTORY DESIGN
**Chair: Kathleen Howell, Purdue University**

### AAS 14 – 233

**A Quick Search Method for Low-Energy Trajectory Options to Near Earth Objects**

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

In this study, the use of low-energy trajectories computed from the invariant manifolds of unstable periodic orbits is explored as a means to transfer from low-Earth orbit to Near Earth Objects. Previous work estimated the maneuvers required to reach these asteroids using planar assumptions, and various other studies have focused on returning an asteroid to Earth's vicinity. In this study, new asteroids are examined using the planar assumption, and three-dimensional effects are included for comparison with these results. Specific cases are examined in more detail, and effects of using the ephemeris are studied. [View Full Paper]

### AAS 14 – 234

**Applications of Gravity Assists in the Bicircular and Bielliptic Restricted Four-Body Problem**

**Kenta Oshima** and **Tomohiro Yanao**, Department of Applied Mechanics and Aerospace Engineering, Waseda University, Tokyo, Japan

We explore two ways of gravity assists concerning three-body energy and two-body energy in the planar restricted four-body problem. The first is concerned with changing dynamical objects of the restricted three-body problem such as energy of orbits and energetically forbidden region via gravity assists within the framework of the restricted four-body problem. As an application, we propose a method of finding nominal transfer trajectories between Lyapunov orbits of different energies without fuel consumption. The second is concerned with revealing time-dependent analogues of invariant manifolds of resonant orbits directly in the restricted four-body problem. For this purpose, we employ the method of Lagrangian coherent structures as a visual aid. We then identify homoclinic and heteroclinic connections of resonant orbits in the restricted four-body problem, which could be applicable to the low-energy exploration of the moons of Jupiter. [View Full Paper]

### AAS 14 – 235

**Flow Control Segment and Lagrangian Coherent Structure Approaches for Application in Multi–Body Problems**

**Cody R. Short**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Daniel Blazevski**, Institute for Mechanical Systems, Department of Mechanical and Process Engineering, Zurich, Switzerland; **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **George Haller**, Institute for Mechanical Systems, Department of Mechanical and Process Engineering, Zurich, Switzerland

Lagrangian Coherent Structures (LCS) are useful for describing the general flow of a particular system, including specific flow regions advantageous to desirable transport options. The underlying theory that leads to the LCS concept applies to any system that exhibits flow, including the Circular Restricted Three–Body Problem (CR3BP) and other astrodynamical systems. Generally, these models require working within a higher–dimensional phase space. Satisfactory identification of LCS in such systems becomes increasingly challenging, but additional information available from the Cauchy–Green Strain Tensor (CGST) supplies contextual cues to aid in this endeavor or for other applications. Maneuvers seeded from initial Flow Control Segments (FCS), a related concept, can lead to desirable trajectory evolution. These segments provide an option for exploring the phase space and improving maneuver costs that take a spacecraft from an initial location to a target destination. Methods for applying this additional information are explored in this paper. [View Full Paper]

## AAS 14 – 236

### Improved Transfers to Earth-Moon $L_3$ Halo Orbits

**Kathryn E. Davis** and **Jeffrey S. Parker**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.;
**Masoud Deilami** and **Eric A. Butcher**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.

This paper presents methods to compute and analyze two-impulse transfers from low-Earth orbit (LEO) to Earth-Moon $L_3$ libration point orbits (LPOs). The first maneuver is executed in LEO and the second is an injection maneuver onto the LPO. Families of transfers are located and evaluated. All transfers computed required at least one lunar flyby. The lunar flyby characteristics are related to the total $C_3$ of the transfer. The results presented represent an improvement from previous work: orbit injection maneuvers are reduced from 130 m/s to 16.55 m/s, and the time of flight is decreased from 44 days to 29 days. [View Full Paper]

## AAS 14 – 237

### F And G Taylor Series Solutions to the Circular Restricted Three Body Problem

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

The Circular Restricted Three-Body Problem is solved using an extension to the classic *F* and *G* Taylor series. The Taylor series coefficients are developed using exact recursion formulas, which are implemented via symbolic manipulation software. In addition, different time transformations are studied in order to obtain an adapted discretization for the three-body problem. The resulting propagation method is compared to a conventional numerical integration method, the Runge-Kutta-Fehlberg integrator, on a set of test scenarios designed to qualitatively represent the different types of three-body motion. The series solution is demonstrated to have comparable performance to the conventional integrator, when considering a variety of circumstances, such as the independent variable, error tolerance, orbit characteristics, and integration scheme. In the variable-step case, for low-fidelity applications, such as preliminary design of trajectories, the *F* and *G* series with no time transformation are shown to be two to three times faster than the conventional integrator in all cases, when selecting an appropriate order. In the fixed-step case, the Sundman time transformations are demonstrated to reduce the number of steps required for convergence by one or more orders of magnitude. This improved discretization confirms the value of regularization in the restricted three-body problem, and suggests the utility of fixed-step integration using Sundman transformed equations of motion. [View Full Paper]

**AAS 14 – 238**

**Near Optimal Feedback Guidance Design and the Planar Restricted Three-Body Problem**

**Joseph Dinius** and **Roberto Furfaro**, University of Arizona, Tucson, Arizona, U.S.A.; **Francesco Topputo**, Politecnico di Milano, Milan, Italy; **Scott Selnick**, University of Arizona, Tucson, Arizona, U.S.A.

In this paper, we present the application of the ZEM/ZEV guidance algorithm to the planar restricted three-body problem (PR3BP). The ZEM/ZEV guidance law as a feedback guidance strategy is presented and applied to the PR3BP. The fuel optimal solution to the PR3BP for a transfer from GTO to $L_1$ in the Earth-Moon system is presented as a point for comparison, showing the near optimality of the closed-loop guidance approach. Challenges of the approach and strategies for implementation in spacecraft mission design are discussed. [View Full Paper]

**AAS 14 – 239**

**Novel Solar Sail Mission Concepts for Space Weather Forecasting**

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

This paper proposes two novel solar sail concepts for space weather forecasting: heliocentric Earth-following orbits and Sun-Earth line confined solar sail manifolds. The first concept exploits a solar sail acceleration to rotate the argument of perihelion such that aphelion, where extended observations can take place, is always located along the Sun-Earth line. The second concept exploits a solar sail acceleration to keep the unstable, sunward manifolds of a solar sail Halo orbit around a sub-$L_1$ point close to the Sun-Earth line. By travelling upstream of space weather events, these manifolds then allow early warnings for such events. The orbital dynamics involved with both concepts will be investigated and the observation conditions in terms of the time spent within a predefined surveillance zone are evaluated. All analyses are carried out for current sail technology (i.e. Sunjammer sail performance) to make the proposed concepts feasible in the near-term. The heliocentric Earth-following orbits show a reasonable increase in useful observation time over inertially fixed, Keplerian orbits, while the manifold concept enables a significant increase in the warning time for space weather events compared to existing satellites at the classical $L_1$ point. [View Full Paper]

**AAS 14 – 240**

**(Paper Withdrawn)**

### AAS 14 – 241

### Using Lunar Swingbys and Libration-Point Orbits to Extend Human Exploration to Mars

**John N. Kidd Jr.** and **Roberto Furfaro**, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.;
**David Dunham**, KinetX, Inc., Greenbelt, Maryland, U.S.A.

This paper will concentrate on one mission profile of particular interest, a manned mission to Mars. Specifically, the study will explore the use of HEOs whose line of apsides can be rotated using lunar swingbys to approximate the $V_\infty$ vector necessary for such a mission, reducing the required energy cost of such a mission. The HEO also provides a convenient and relatively fast location for rendezvous with crew, or to add propulsion or cargo modules, a technique that we call "Phasing Orbit Rendezvous." From a HEO, a propulsive maneuver, considerably smaller than that needed from a circular low-Earth orbit, can be applied at the right perigee to send the spacecraft on the appropriate departure asymptote. A propulsive maneuver at perigee can be used to re-capture the spacecraft into a loosely-bound orbit at the return, perhaps assisted by a lunar swingby. Earth-Moon (and possibly Sun-Earth) libration point orbits and double-lunar swingby orbits will be used, along with time to change the orbital orientation between missions. There might be wait times of several months to years between missions, when the interplanetary spacecraft could be "parked" in a small-amplitude Lissajous orbit about a libration point, similar to that flown by the WMAP mission. [View Full Paper]

### AAS 14 – 242

### Investigating the Optimization of Mid-Course Maneuvers to Earth-Moon $L_2$ Libration Orbit

**Jennifer Dowling** and **Jeffrey Parker**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.

Baseline trajectories to an Earth-Moon $L_2$ libration orbit for crewed missions have been created in support of an advanced Orion mission concept. Various transfer durations and orbit insertion locations have been evaluated. The trajectories often include a deterministic mid-course maneuver after a powered lunar flyby that decreases the overall change in velocity in the trajectory. This paper presents the application of primer vector theory to study the existence, location, and magnitude of the mid-course maneuver in order to understand how to build an optimal transfer to an $L_2$ orbit.
[View Full Paper]

## SESSION 5: SPACECRAFT AUTONOMY
**Chair: Fu-Yuen Hsiao, Tamkang University**

### AAS 14 – 243

**Spinner Spacecraft Propulsion Model for Magnetospheric MultiScale Mission (MMS) Flight Dynamics Applications**

**Laurie M. Mann**, **Conrad Schiff** and **Henry W. Mulkey**, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

The Magnetospheric MultiScale Mission (MMS) consists of four spacecraft flying in highly eccentric orbits with the goal to further our understanding of Earth magnetic reconnection events. Throughout its two and a half year mission life-time, each MMS spacecraft is predicted to perform approximately 200 maneuvers. This paper focuses on the flight dynamics propulsion model that is used to generate the Delta-V maneuver plan uploaded to the spacecraft. The purpose of this model is to ensure enough margins are allocated during the planning process so that the on-board controller can keep up with the desired imparted impulse, thus preventing a potential abort of the maneuver. An additional consideration is accurate estimation of propellant mass depletion during the maneuver reconstruction process. [View Full Paper]

### AAS 14 – 245

**Orbit Control and Hovering in Asteroid Dynamical Enviroments Using Higher Order Sliding Control Theory**

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

Close proximity operations around small bodies in general and asteroids in particular are extremely challenging due to their uncertain dynamical environment. In this paper, we apply Higher Order Sliding Control (HOSC) theory to devise a class of 2-sliding homogeneous controllers that are suitable for autonomous orbit control and hovering in highly uncertain dynamical environments typically founds around asteroids. The class of controllers that can be constructed using the HOSC theory are shown to be globally finite-time stable against perturbations with known upper bound. The properties of the proposed 2-sliding controller and its contractive properties are both demonstrated both via a Lyapunov-based theoretical analysis and via simulation of closed-loop trajectories. The latter involves simulating the motion of the controlled spacecraft in the dynamical environment around Eros to demonstrate the effectiveness of the control algorithm for autonomous hovering and other close-proximity operations around asteroids. [View Full Paper]

**AAS 14 – 246**

**Fault Detection and Isolation Strategy for Redundant Inertial Measurement Units**

**Renato Zanetti**, Vehicle Dynamics and Control, The Charles Stark Draper Laboratory, Houston, Texas, U.S.A.; **Abran Alaniz**, Dynamic Systemss and Control, The Charles Stark Draper Laboratory, Houston, Texas, U.S.A.; **Louis Breger**, Tactical Guidance and Control, The Charles Stark Draper Laboratory, Cambridge, Massachusetts, U.S.A.; **Ian Mitchell**, Dynamic Systemss and Control, The Charles Stark Draper Laboratory, Houston, Texas, U.S.A.; **Richard Phillips**, The Charles Stark Draper Laboratory, Cambridge, Massachusetts, U.S.A.

Aerospace vehicles are often required to be two-fault tolerant in order to be man-rated. This paper presents a two-fault tolerant fault detection and isolation algorithm for a set of four redundant inertial measurement units (IMUs). The paper derives the fault detection thresholds. The algorithm tests the IMU data after it is processed by an infinite impulse response filter. Two tests are performed; the first applies a low cut-off frequency filter to the data in order to detect biases and slowly growing biases. The second test is performed with a high cut-off frequency filter in order to detect off-nominal abrupt changes in IMU errors. [View Full Paper]

**AAS 14 – 247**

**Autonomous Position Estimation for Lunar Orbiters Using a Visible Camera**

Stoian Borissov and Daniele Mortari, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

This paper presents a method for autonomous attitude and position (pose) estimation for spacecraft in lunar orbit, which may be used when a spacecraft loses communication with Earth. Using only on-board equipment, namely, a visible camera with the capability of taking multiple pictures featuring the Moon and stars, pose estimation is performed. A set of pictures of the stars will be used to estimate the direction towards the Moon, while a picture of the Moon will be used to estimate the distance between the observer and the Moon. Together, these will provide enough information to estimate inertial position. [View Full Paper]

**AAS 14 – 248**
**(Paper Withdrawn)**

## AAS 14 – 249

### Model Predictive Control and Extended Command Governor for Improving Robustness of Relative Motion Guidance and Control

**Christopher Petersen**, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.; **Andris Jaunzemis**, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.; **Morgan Baldwin**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland Air Force Base, New Mexico, U.S.A.; **Marcus Holzinger**, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.; and **Ilya Kolmanovsky**, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.

The paper describes two approaches to improving on-board robustness of spacecraft relative motion guidance and control. The first approach is based on Model Predictive Control (MPC), and this paper demonstrates its capability for robust trajectory execution by changing the environment with a sudden obstacle appearing along its path. The second, novel approach uses an Extended Command Governor (ECG) that augments a nominal LQ controller. The ECG modifies commanded set-points to the inner loop LQ controller when it becomes necessary to avoid constraint violation. Simulations are used to compare the two approaches and experimental results of MPC, based on an omnibot system developed for validation of spacecraft relative motion control algorithms, are reported. [View Full Paper]

## AAS 14 – 250

### The Adaptive Entry Guidance Based on 3D Obtainable Space Concept

**Erlong Su**, **Jianjun Luo** and **Baichun Gong**, College of Astronautics, Northwestern Polytechnical University, Xi'an, China

A three-dimension obtainable space concept for entry guidance subjected to path constraints is developed in this paper. The key characteristics of this method is that it can transform the path constraints of heating rate and dynamic pressure into control variable constraints which are bank angle and attack angle, obtaining a three-dimensional control variables space. The transformation can substantially simplify the entry guidance and trajectory design especially online design. The proportional terminal guidance law is introduced in the entry guidance which could fulfill the integrated design of entry guidance and terminal guidance through applying the 3D obtainable space concept. [View Full Paper]

**AAS 14 – 251**

**Semi-Analytical Guidance Algorithm for Autonomous Close Approach to Non-Cooperative Low-Gravity Targets**

**Paolo Lunghi**, **Michèle Lavagna** and **Roberto Armellin**, Aerospace Science and Technology Department, Politecnico di Milano, Milano, Italy

An adaptive guidance algorithm for close approach to and precision landing on uncooperative low-gravity objects (e.g. asteroids) is proposed. The trajectory, updated by means of a minimum fuel optimal control problem solving, is expressed in a polynomial form of minimum order to satisfy a set of boundary constraints from initial and final states and attitude requirements. Optimal guidance computation, achieved with a simple two-stage compass search, is reduced to the determination of three parameters, time-of-flight, initial thrust magnitude and initial thrust angle, according to additional constraints due to actual spacecraft architecture. A NEA landing mission case is analyzed. [View Full Paper]

**AAS 14 – 252**

**Feedback and Iterative Learning Control With Disturbance Estimators**

**Anil Chinnan**, Columbia University, New York, New York, U.S.A.;
**Minh Q. Phan**, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, U.S.A.; **Richard W. Longman**, Department of Mechanical Engineering, Columbia University, New York, New York, U.S.A.

Iterative learning control (ILC) and feedback control (FBC) are fundamentally different in terms of their objectives and limitations. An iterative learning controller can compensate for unknown repeating errors and disturbances, but it is not suited to handle non-repeating errors and disturbances, which can be more effectively handled by a feedback controller. A combination of feedback and iterative learning controllers would be an ideal control strategy. This paper shows how a one-time step behind disturbance estimator and one-repetition behind disturbance estimator can be incorporated in such a feedback and iterative learning controller combination. [View Full Paper]

**AAS 14 – 253**

**Idiosyncrasies in the Inverse Models of Digital Skip Step Finite Time Systems**

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

Iterative learning control (ILC) iterates with the real world to find the command to a control system to produce zero tracking error at each time step for a specific trajectory. ILC can produce high precision tracking of fine pointing scanning maneuvers in spacecraft. Asking for zero error at sample times usually creates an unstable inverse problem when the input comes through a zero order hold. We use multiple zero order holds between addressed samples times to address this problem. But other anomalous singular values appear in the input-output matrix that cause difficulties to the inverse problem. Behaviors and comparison of original and new anomalous singular values and associated singular vectors are studied. Then not asking for zero error for a small number of initial time steps is shown to eliminate all anomalous singular values. This can form the basis for producing well posed inverse problems for ILC design.
[View Full Paper]

## SESSION 6: NAVIGATION
## Chair: Brian Page, KinetX Aerospace

**AAS 14 – 244**

**Solar and Thermal Radiation Pressure Models and Flight Evaluation for IKAROS Solar Sail**

**Jozef van der Ha**, Consultant, Deming, Washington, U.S.A.; **Yuya Mimasu**, **Yuichi Tsuda** and **Osamu Mori**, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan

This paper gives a detailed evaluation of the solar and thermal radiation accelerations acting on the IKAROS solar sail and its spacecraft body during its operational mission from June to December 2010. In particular, the predicted temperatures are compared with actual in-flight measurements on the sail membrane as well as on the body. The results show fairly good correspondences in most cases but a few appreciable deviations have also been observed. The simulation results indicate that the magnitude of the thermal radiation perturbations on the solar sail trajectory is only about one percent of the solar radiation and may be neglected in view of the considerable uncertainties in the solar radiation force. [View Full Paper]

## AAS 14 – 254

### Expected Performance of the Deep Space Atomic Clock Mission

**Todd A. Ely**, **David Murphy**, **Jill Seubert**, **Julia Bell** and **Da Kuang**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Deep Space Atomic Clock mission is developing a small; highly stable mercury ion atomic clock with an Allan deviation of at most 1e-14 at one day, with current estimates near 3e-15. This stability enables one-way radiometric tracking data with accuracy equivalent to or better than (under certain conditions) current two-way deep space tracking data; allowing a shift to a more efficient and flexible one-way deep space navigation architecture. The project is building a demonstration unit of the mercury ion atomic clock and the associated payload that will be used to validate the clock's performance. The payload will be launched in early-2016 into low Earth orbit as a hosted payload on the Surrey Satellite Technology's Orbital Test Bed spacecraft for a year-long demonstration mission. This study presents the preliminary estimates of the orbit and clock determination that the mission expects to achieve. [View Full Paper]

## AAS 14 – 255

### The Evolution of Deep Space Navigation: 1999–2004

**Lincoln J. Wood**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The exploration of the planets of the solar system using robotic vehicles has been underway since the early 1960s. During this time the navigational capabilities employed have increased greatly in accuracy, as required by the scientific objectives of the missions and as enabled by improvements in technology. This paper is the third in a chronological sequence dealing with the evolution of deep space navigation. The time interval covered extends from the 1999 launch of the Stardust spacecraft to comet P/Wild 2 through the arrival of the Cassini spacecraft at Saturn in 2004. The paper focuses on the observational techniques that have been used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods that have been employed, tracing their evolution through eight planetary missions. [View Full Paper]

## AAS 14 – 256

**Navigation Filter Simulator Development for Small Body Proximity Operation**

**Peter C. Lai**, Data Handling System – Satellite Engineering, Globalstar Inc., Milpitas, California; **David S. Bayard**, Guidance and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

A simulator is developed to test a vision-based on-board navigation filter algorithm relevant to space exploration of small bodies such as asteroids and comets. The navigation filter algorithm was developed in earlier references and includes many data types relevant to small body proximity operations. These data types include the Landmark Table, Paired Feature Table, and Range Measurement Table. The first two data types use vision-based camera measurements, while the third consists of multi-beam altimeter measurements. The paper presents the simulation architecture and test scenarios to validate the simulation code, along with the derivation of a range dependent measurement noise. The MATLAB simulation environment was developed in the form of modules for portability and reusability, and is intended for future integration into a robotic testbed with coding into C/C++ for real-time applications. [View Full Paper]

## AAS 14 – 257

**Linear and Unscented Covariance Analysis for Spacecraft Close Proximity Relative Navigation**

**Jacob E. Darling**, **James S. McCabe**, **Henry J. Pernicka** and **Kyle J. DeMars**, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.

Linear and unscented covariance analyses are implemented to compare the nominal performance of an extended and unscented Kalman filter for estimating the relative position and velocity of a deputy spacecraft using two camera line-of-sight measurements from a chief spacecraft, as well as the position, velocity, and attitude of the chief spacecraft. Dead reckoning of IMU data is used with external aiding from GPS and magnetometer measurements aboard the chief spacecraft. The ratio of nongravitational acceleration acting on the deputy spacecraft with respect to the chief spacecraft is included in order to stochastically include the effects of perturbations to relative motion. Camera specifications, such as resolution and baseline, are investigated to determine their effects on the nominal performance. [View Full Paper]

## AAS 14 – 258

**(Paper Withdrawn)**

**AAS 14 – 259**

**Performance Evaluation of the Target-Star Angles Based Relative Navigation Method**

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

The target-star angles based relative navigation method can be used for far or medium range relative navigation. The measurement information contains relative distance and the target-star angles. The target-star angle refers to the angle between the line of sight vector of the target and the line of sight vector of the reference star. An overall architecture and detailed algorithms for the proposed method are introduced. Six groups of Monte Carlo simulations with different amounts of reference stars and different opening angles are undertaken to evaluate the influence of the amount of the reference stars. The error distributions of the relative bearings on the imaging sensor's focal plane are computed to make an additional investigation about the opening angles.
[View Full Paper]

**AAS 14 – 260**

**Finite-Time Observer for Rigid Spacecraft Motion Over an Asteroid**

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

A finite-time observer design for translational and rotational motion states of a rigid body modeled for a spacecraft and the parameters of an asteroid is presented. This nonlinear observer presents almost global convergence of the state and the parameter estimations in finite time using the state measurements of the rigid spacecraft's pose and velocities. The states include the pose and velocities of a rigid body of a spacecraft while the parameters include the second order and degree of gravity coefficients, and the gravitational parameter of an asteroid. The observer design is based on the use of the exponential coordinates to describe rigid body pose estimation errors on SE(3), which provides an almost global description of the pose estimation error. The finite-time convergence of the state and gravity parameters estimations of the observer is verified using a Lyapunov analysis on the nonlinear state space of the motion. Numerical simulation results confirm this analytically obtained convergence property and the robustness in the presence of measurement noises. [View Full Paper]

**AAS 14 – 261**
**(Paper Withdrawn)**

## AAS 14 – 262

**A Novel Angles-Only Relative Navigation Algorithm for Space Non-Cooperative Target On-Orbit Servicing**

**Baichun Gong**, **Jianjun Luo** and **Jianping Yuan**, College of Astronautics, Northwestern Polytechnical University, Xi'an China; **Wenyong Zhou**, Beijing Institute of Astronautical Systems Engineering, Beijing, China

The theory substance of angles-only relative navigation for autonomous orbital rendezvous to non-cooperative target is discussed. A novel algorithm based on GPS absolute positioning and CCD relative angles of LOS measuring is presented, which is aided by an initial value of the relative distance including error from ground or space surveillance system only once. Emphasis is placed on the relative distance reconstruction and angles-only navigation filter development to determine relative position and velocity between a passive non-cooperative target and a maneuvering servicer. A recursive estimation formula of relative distance is derived from the differential value between the sequences of GPS positioning at two different epochs, based on triangle principle, while the recursive errors are analyzed by theoretical derivation and numerical simulation. Then the navigation filter model is established, and an Extended Kalman filter is selected to process angular measurements from a CCD camera along with relative distance obtained recursively from GPS to estimate the relative states. The proposed algorithm is systemically tested by numerical simulation, and robustness about the error of initial relative distance value aided is evaluated. [View Full Paper]

## AAS 14 – 263

**Navigation Design and Analysis for the Orion Earth-Moon Mission**

**Christopher D'Souza** and **Renato Zanetti**, Aeroscience and Flight Mechanics Division, NASA Johnson Space Center, Houston, Texas, U.S.A.

This paper details the design of the cislunar optical navigation system being proposed for the Orion Earth-Moon (EM) missions. In particular, it presents the mathematics of the navigation filter. The unmodeled accelerations and their characterization are detailed. It also presents the analysis that has been performed to understand the performance of the proposed system, with particular attention paid to entry flight path angle constraints and the $\Delta V$ performance. [View Full Paper]

## AAS 14 – 264

**(Paper Withdrawn)**

## SESSION 7: TRAJECTORY DESIGN I

**Chair: Yanping Guo, Johns Hopkins University Applied Physics Laboratory**

### AAS 14 – 265

### Forced Precession Orbit Departing From Keplerian Orbit Under Continuous Normal Thrust

**Jing Cao** and **Jianping Yuan**, School of Astronautics, Northwestern Polytechnical University, Xi'an, China; **Yong Shi**, Mechanical Engineering Department, Stevens Institute of Technology, Hoboken New Jersey, U.S.A.; **Jianjun Luo**, School of Astronautics, Northwestern Polytechnical University, Xi'an, China; **Zhiguo Zhang**, School of Aerospace, Tsinghua University, Beijing, China

A novel non-Keplerian orbit, known as forced precession orbit, resulting from continuous normal thrust is proposed motivated by the precession of gyroscope. We study the orbits departing from both Keplerian circular orbit and elliptical orbit. For the circular case, the forced precession rule we defined indicates that constant normal thrust is required, while for the elliptical case, periodic normal thrust is required. Using a quaternion-based formulation, the orbital motion in the circular case can be solved analytically, which is not true of the elliptical case. Therefore, numerical analysis and Floquet theory are employed to determine the orbital characteristics in the elliptical case. The results indicate that the forced precession orbit in the circular case is a displaced orbit. The long-term evolution of the forced precession orbit in the elliptical case exhibits a quasi-bird's nest geometry with upper and lower circular boundaries, the radii of which can be determined using the integral constants. Using appropriate initial orbital parameters, a quasi-periodic, displaced orbit parallel to the equatorial plane with zonal coverage can be obtained in the elliptical case. [View Full Paper]

### AAS 14 – 266

### Optimal Impulsive Rendezvous With Terminal Tangent Burn Between Elliptic and Hyperbolic Orbits Considering the Trajectory Constraints

**Wenbo Zhang**, **Yue Chen**, **Xin Sui** and **Ningfei Wang**, School of Aerospace Engineering, Beijing Institute of Technology, Haidian District, Beijing, P.R. China

In cycler architectures, a crew "taxi" docks with the interplanetary transfer vehicle on a hyperbolic flyby trajectory. For safety considerations, a tangent orbit technique is adopted in impulsive rendezvous. Reachable domain for transfer orbit with a terminal tangent burn is first analyzed. Then two-impulse transfers with terminal tangent burn between elliptic and hyperbolic orbits are optimized in term of semimajor axes, eccentricity, inclination, and the relative position of the lines of apsides and their effects on the optimal transfer orbits are summarized. Finally, based on the results of two-impulse orbital transfer, feasible transfer trajectories are constructed to serve as initial guesses for determining constrained optimal impulsive rendezvous trajectories from a parking orbit to a target hyperbolic orbit. Numerical simulation results can be applied to the preliminary design on hyperbolic rendezvous. [View Full Paper]

**AAS 14 – 267**

**Design of End-to-End Trojan Asteroid Rendezvous Tours Incorporating Potential Scientific Value**

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

The Sun-Jupiter Trojan asteroids are celestial bodies of great scientific interest as well as potential natural assets offering mineral resources for long-term human exploration of the solar system. Previous investigations have addressed the automated design of tours within the asteroid swarm and the transition of prospective tours to higher-fidelity, end-to-end trajectories. The current development incorporates the route-finding Ant Colony Optimization (ACO) algorithm into the automated tour generation procedure. Furthermore, the potential scientific merit of the target asteroids is incorporated such that encounters with higher value asteroids are preferentially incorporated during sequence creation. [View Full Paper]

**AAS 14 – 268**
**(Paper Withdrawn)**

**AAS 14 – 269**

**Explore Europa by the Jovian Magnetic Lorentz Force**

**Zhiguo Zhang**, **Shengping Gong** and **Junfeng Li**, School of Aerospace, Tsinghua University, Beijing, China

In this paper, the Lorentz force in Jupiter's magnetic field is used to design Europa tour mission. The equatorial orbits of charged spacecraft in three-body axis-aligned nontilted-dipole magnetic field model are analyzed and the results show that the libration point L1 and L2 become nearer or further away from Europa with the variable size and polarity of the charge. The character of the libration point is similar to that in the Saturn-Enceladus system. A bang-bang charge control method is used to send the spacecraft to the new point L2 which is closer to Europa than the classical L2 point, where the spacecraft can be captured by Europa more easily. Further, the endgame problem is discussed for a new mission profile that the spacecraft is separated into two parts at the new L2 point, where one is charged and the other is not. The separation can be realized just using momentum conservation through a spring rigging. One section can speed up to form the eight-shaped Lissajous orbit, and the other section is controlled to form the Europa orbit using charge to increase and decrease the orbital radius. Finally, the analytical and numerical methods are used to give the fast and accurate design of the transfer trajectory, respectively. The spacecraft from the L2 point of Jupiter-Ganymede to the new L2 point of Jupiter-Europa only takes less than 30 days with q/m less than 0.5C/kg. The separate mass ratio about 1:1 is needed to form the Europa orbit and Lissajous orbit. [View Full Paper]

AAS 14 – 270

**Autonomous Trajectory Redesign for Phobos Orbital Operations**

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

Aside from interest in the moons themselves, Phobos and Deimos provide a natural transition between asteroid exploration and eventual manned missions to the surface of Mars. Among the many challenges of such a mission, the need to switch between different orbit families in an unstable environment and the rapid divergence from reference trajectories requires action faster than ground based planning or simple control can provide. Orbital operations at Phobos will likely require autonomous action in order to be successful. A redesign tool based on heuristic search and sequential convex programming is shown to re-plan or correct important transfers in a rapid and robust manner, even with very large perturbations to the expected initial conditions. Changes to earlier approaches are detailed, as well as challenges specifically posed by Phobos.
[View Full Paper]

**AAS 14 – 271**
**(Paper Withdrawn)**

AAS 14 – 272

**Automated Patch Point Placement for Spacecraft Trajectory Targeting**

**Galen Harden**, **Amanda Haapala** and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.;
**Belinda Marchand**, Adjunct Professor, Purdue University, Austin, Texas, U.S.A.

Autonomous targeting and guidance, specifically that which relies on iterative gradient-based processes, is sensitive to the quality of the startup guess or estimate and the underlying dynamical sensitivities. These startup arcs are often delivered as a collection of “patch states”, i.e., a discretized representation of the overall trajectory in the full dynamical model. The goal of this work is to devise a systematic process by which to quantify and characterize the dynamical sensitivity of these points, and use this scheme to devise a metric that facilitates the systematic determination of their placement along the path prior to the application of optimal or sub-optimal corrections processes. The purpose of this strategy, ultimately, is to improve the performance of gradient based targeting and guidance algorithms in offline autonomous scenarios where human intervention is not plausible. The approach leverages Local Lyapunov Exponents in devising the metric and process by which patch states are systematically located. [View Full Paper]

**AAS 14 – 273**

**A Continuation Method for Converting Trajectories From Patched Conics to Full Gravity Models**

**Nicholas Bradley** 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.

A method is introduced to transition space trajectories from low fidelity patched conics models to full-ephemeris *n*-body dynamics. The algorithm incorporates a continuation method that progressively re-converges solution trajectories in systems with incrementally higher fidelities. Continuation is accomplished through the variation of a control parameter, which is tied to body parameters such as ephemerides, mass, minimum flyby altitude, and sphere of influence size. The intermediate models provide a continuous and differentiable path between solutions in the simplified and *n*-body dynamics. Each successive step preserves the individual flyby properties by altering periapsis flyby states and body masses, ensuring that the final converged solution is qualitatively similar to the initial guess. A similar approach to this methodology may be taken with any simplified starting guess, such as a restricted three-body model. Trajectories computed using the patched conics conversion method presented here may include gravity assists and rendezvous with any number of target bodies, so the method is ideal for constructing interplanetary or intermoon tour missions. [View Full Paper]

**AAS 14 – 274**

**Three Problems in Space Flight Mechanics Approached Using the Multipoint Extension of Pontryagin's Maximum Principle**

**Alan Zorn**, Department of Aeronautics and Astronautics, Stanford University, Stanford, California, U.S.A.; **Matt West**, Department of Mechanical Science and Engineering, University of Illinois, Urbana-Champaign, Illinois, U.S.A.

A new result in nonlinear optimal control is used to approach three problems in space flight mechanics. It is shown that our method provides a unified theory to solve these different problems. Our theory also suggests interesting and useful variations and extensions of these problems that have hitherto been posed or solved. [View Full Paper]

## SESSION 8: ASTEROID RETRIEVAL AND MITIGATION
**Chair: Anastassios Petropoulos,Jet Propulsion Laboratory**

### AAS 14 – 275
**Interplanetary Superhighways: Cheaper Roads To Deflect Apophis**

**Reza Raymond Karimi** and **David C. Hyland**, Department of Aerospace Engineering, Texas A&M University, 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 potential Earth-crossing objects. The trajectory of the spacecraft will be designed based on the concept of interplanetary Superhighways (Patched Three-body problem) in which the space mission will be possible using very low energy and the results are compared to that of Patched Conic two-body problem. The propulsion system will be continuous and low thrust. [View Full Paper]

### AAS 14 – 276
**What Does it Take to Capture an Asteroid?**
**A Case Study on Capturing Asteroid 2006 $RH_{120}$**

**Hodei Urrutxua**, Space Dynamics Group, School of Aeronautical Engineering, Technical University of Madrid (UPM), Spain; **Daniel J. Scheeres**, Celestial and Spaceflight Mechanics Laboratory, Colorado Center for Astrodynamics Research, University of Colorado at Boulder, Colorado, U.S.A.; **Claudio Bombardelli**, **Juan L. Gonzalo** and **Jesús Peláez**, Space Dynamics Group, School of Aeronautical Engineering, Technical University of Madrid (UPM), Spain

The population of “temporarily captured asteroids” offers attractive candidates for asteroid retrieval missions. Once captured, these asteroids have lifetimes ranging from a few months up to several years in the vicinity of the Earth. One could potentially extend the duration of such temporary capture phases by acting upon the asteroid with slow deflection techniques that conveniently modify their trajectories, in order to allow for an affordable access to an asteroid for in-situ study. In this paper we present a case study on asteroid 2006 $RH_{120}$, which got temporarily captured in 2006-2007 and is the single known member of this category up to date. We study what it would have taken to prolong its capture and estimate that deflecting the asteroid with 0:27 N for less than 6 months and a total $\Delta V$ barely 32 m/s, would have sufficed to extend the capture for over 5 additional years. [View Full Paper]

## AAS 14 – 277

### Asteroid Retrieval Via Direct Launch and Solar Electric Propulsion

**Jacob A. Englander**, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; Eric H. Cardiff, Propulsion Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

This paper discusses a spacecraft design concept and mission optimization for missions to 12 different asteroids. Mission concepts with different electric propulsion systems were considered for optimization by the Evolutionary Mission Trajectory Generator (EMTG) code. The optimization was conducted to find the latest possible launch to reach said asteroids using engine models with both variable thrust and specific impulse. A range of propulsion systems, powers, launch vehicles, and target asteroids were studied. Results are presented for the required trajectories and the required propellant.
[View Full Paper]

## AAS 14 – 278

### Comprehensive Modeling of the Effects of Hazardous Asteroid Mitigation Techniques

**D. J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **E. I. Asphaug**, Department of Planetary Science, Arizona State University, Tempe, Arizona, U.S.A.; **C. Bombardelli**, Technical University of Madrid, Spain; **S. Chesley**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **A. Doostan**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **E. Herbold**, Lawrence Livermore National Laboratory, Livermore, California, U.S.A.; **B. Jones**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **D. Korycansky**, Department of Planetary Science, Arizona State University, Tempe, Arizona, U.S.A.; **J. W. McMahon**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **P. Miller**, **J. M. Owen**, Lawrence Livermore National Laboratory, Livermore, California, U.S.A.; **P. Sánchez**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

A plan and initial progress towards a program of fundamental research on the modeling of hazardous asteroid mitigation is described. This work focuses on computational modeling of outcomes from previously developed asteroid mitigation techniques. Our goal is to evaluate these techniques accounting for the expected and predicted range of asteroid geophysical and dynamical properties. This work defines a necessary and fundamental step for the design and evaluation of future mitigation experiments and attempts. It also enables the identification of necessary technology for the detection of mitigation outcomes to use as a fundamental metric in our models and evaluations.
[View Full Paper]

## AAS 14 – 279

### Robust Deflection Strategies of Near Earth Asteroids Under Uncertainties

**Mai Bando**, **Yuki Akiyama** and **Shinji Hokamoto**, Department of Aeronautics and Astronautics, Kyushu University, Nishu-ku, Fukuoka, Japan

In this paper, an approach to optimize deflection mission of Near Earth asteroids under uncertainty is proposed based on control theoretical framework. By using the nonlinear mapping from initial deviation to the final deviation, the performance index J which is expressed as a function of the distance of the Earth in the Earth's closest approach time is minimized for the worst case initial condition. We also formulate the robust orbital transfer problem of kinetic impactor spacecraft where the initial state estimation error exists. [View Full Paper]

## AAS 14 – 280

### Asteroid Target Selection and Orbital Manipulation Innocuity for Deflection Demonstration Missions

**J. P. Sánchez**, Department of Applied Mathematics I, Universitat Politècnica de Catalunya, Barcelona, Spain

In recent years, space agencies have begun to seriously consider launching demonstration mission for some of the asteroid orbital deflection technologies that have been discussed in the scientific literature. Consequently, several mission studies have already been carried out. This paper attempts to gain new insights into target selection process by analysing the orbital evolution of a large set of notional accessible asteroids covering all type of NEO families. The evolutions of the unperturbed and anthropogenic orbits are compared, and a measure of the resilience of a given orbit to anthropogenic manipulation is taken (i.e., orbital innocuity). The results show that pruning criteria such as considering only Amor objects (i.e., non-Earth-crossers) reduce unnecessarily the population of potential suitable targets and that within large regions of Earth-crossing orbital space asteroids could be found that are both accessible and safe to manipulate from the standpoint of Earth impact risk. [View Full Paper]

**AAS 14 – 281**

**Suborbital Intercept and Fragmentation of Asteroids With Very Short Warning Times**

**Ryan Hupp**, **Spencer Dewald** and **Bong Wie**, Asteroid Deflection Research Center, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

The threat of an asteroid impact with very short warning times (e.g., 1 to 24 hrs) is a very probable, real danger to civilization, yet no viable countermeasures currently exist. The utilization of an upgraded ICBM to deliver a hypervelocity asteroid intercept vehicle (HAIV) carrying a nuclear explosive device (NED) on a suborbital interception trajectory is studied in this paper. Specifically, this paper focuses on determining the trajectory for maximizing the altitude of intercept. A hypothetical asteroid impact scenario is used as an example for determining simplified trajectory models. Other issues are also examined, including launch vehicle options, launch site placement, late intercept, and some undesirable side effects. It is shown that silo-based ICBMs with modest burnout velocities can be utilized for a suborbital asteroid intercept mission with an NED explosion at reasonably higher altitudes (> 2,500 km). However, further studies will be required in the following key areas: i) NED sizing for properly fragmenting small (50 to 150 m) asteroids, ii) the side effects caused by an NED explosion at an altitude of 2,500 km or higher, iii) the rapid launch readiness of existing or upgraded ICBMs for a suborbital asteroid intercept with short warning times (e.g., 1 to 24 hrs), and iv) precision ascent guidance and terminal intercept guidance. It is emphasized that if an earlier alert (e.g., > 1 week) can be assured, then an interplanetary intercept/fragmentation may become feasible, which requires an interplanetary launch vehicle.

[View Full Paper]

**AAS 14 – 282**

**(Paper Withdrawn)**

**AAS 14 – 283**

**Low-Thrust Trajectory Optimization for Asteroid Exploration, Redirect, and Deflection Missions**

**Sam Wagner** and **Bong Wie**, Asteroid Deflection Research Center, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

Recent advances in ultra-lightweight solar sails and high-power solar electric propulsion systems are stimulating a renewed interest in low-thrust interplanetary missions. Such interest includes, the Asteroid Redirect Mission (ARM), which is an robotic mission concept with the goal of returning a small (approximately, 7 m diameter, 500 ton) asteroids, to cis-lunar space using a high-power (40-kW class) solar electric propulsion (SEP) system. This paper describes an efficient low-thrust trajectory optimization solver that employs a new hybrid optimization solver. The new solver combines evolutionary programming for global optimization and traditional calculus based method for local optimization. The final solver is able to solve low-thrust optimization and high-thrust trajectory optimization problems. The solver will be used to determine feasible asteroid redirect missions as well as low-thrust planetary defense demonstration missions.
[View Full Paper]

**AAS 14 – 284**
**(Paper Withdrawn)**

**AAS 14 – 285**

**Nuclear Explosion Energy Coupling Models for Optimal Fragmentation of Asteroids**

**Pavithra Premaratne**, **Ben J. Zimmerman**, **Christian Setzer**, **Jake Harry** and **Bong Wie**, Asteroid Deflection Research Center, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

This paper examines both Tillotson and Jones-Wilkins-Lee (JWL) based energy coupling models, that are often used by various hydrodynamic codes for simulating the effects of high energy explosives. A subsurface nuclear explosion has been known to be 20 times more efficient than a contact burst. Both in-house and commercial AUTODYN hydrodynamic codes are used to validate such a known high efficiency factor of subsurface nuclear explosions. Several test cases are presented, illustrating good agreement with the AUTODYN software. In addition, a new approach for modeling high energy explosives is presented and compared with analytic results and simulations by AUTODYN. Our preliminary results indicate a maximum efficiency factor of only 12 when comparing subsurface versus contact blasts. [View Full Paper]

## SESSION 9: ORBIT DETERMINATION I
### Chair: Laureano Cangahuala, Jet Propulsion Laboratory

**AAS 14 – 286**

**Second Order Nonlinear Initial Orbit Determination for Relative Motion Using Volterra Theory**

**Brett Newman**, Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, Virginia, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.;
**Ethan Pratt**, Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, Virginia, U.S.A.

Application of Volterra multi-dimensional convolution theory to the nonlinear unperturbed circular relative motion initial orbit determination problem is considered in this paper. A series of azimuth-elevation angular measurements locating the deputy with respect to the chief are coupled through the observation geometry with an analytic second order three-dimensional time dependent solution for the relative motion in terms of linear, quadratic, and bilinear combinations of the deputy initial conditions and chief orbital elements. The resulting set of nonlinear measurement equations are analyzed, formulated, and solved in various ways. Methods range from direct solution of the nonlinear equations to reformulation as an equivalent set of linear equations with constraints solved by matrix decomposition and computation of an unknown scaling factor. By using a nonlinear dynamics model with angular measurements, the problem of unobservable states when using a linear model is avoided. In ideal cases with zero sensor noise and zero plant noise, the method recovers the initial state exactly, within the second order framework. With non-zero noise, the initial orbit determination technique recovers the initial state to a level of precision, depending on the validity of the second order framework, that could be passed on to a refined precision orbit determination technique. Although numerical examples are offered, the primary focus of the paper is to lay the foundations of a new and promising method for relative initial orbit determination. [View Full Paper]

## AAS 14 – 287

### Sequential Orbit Determination Using Satellite Laser Ranging

**David A. Vallado**, Center for Space Standards and Innovation, Analytical Graphics Inc., Colorado Springs, Colorado, U.S.A.; **James Woodburn**, Analytical Graphics Inc., Exton, Pennsylvania, U.S.A.; **Florent Deleflie**, Geodesy Research Group (GRGS), Institut de mecanique celeste et de calcul des ephemerides (IMCCE), Observatoire de Paris, France

Satellite Laser Ranging (SLR) is an extremely precise method of tracking satellites that is publicly available. The Orbit Determination Toolkit (ODTK) from Analytical Graphics Inc. (AGI) provides precision orbit determination using an extended Kalman-like filter in combination with different methods of smoothing, an approach requiring parameters that are not generally specified by batch-type estimation. The relevant features accounted for in SLR orbit generation are summarized. Ephemerides generated using ODTK are then compared against definitive orbits from International Laser Ranging Service (ILRS) Analysis Centers to understand the accuracy achieved via the particular setup used, and statements are made concerning relative accuracy and the cause of any differences. [View Full Paper]

## AAS 14 – 288

### Preliminary Determination of the Geocentric Earth Flyby Path of Asteroid 2012 DA14

**Roger L. Mansfield**, Astronomical Data Service, Colorado Springs, Colorado, U.S.A.

This paper presents a method of initial orbit determination (IOD) for use with short arcs of deep-space, angles-only observations. The method is then used to determine the Earth flyby path of the asteroid 2012 DA14 on 2013 February 15, as an extreme example. (The asteroid was inbound and 150-116 Earth radii distant from Earth during the time span of the observations.) The solution is obtained in geocentric coordinates, rather than heliocentric, to emphasize the significance, for Earth, of close-Earth asteroid encounters. Being founded in the work of Paul Herget, the method uses all of the available observations in the arc, not just three, as with classical IOD methods. But when only three suitably-spaced observations are available, it provides an exact, two-body fit. The method is modular with respect to the Lambert solution. It is therefore a schema or framework for preliminary orbit determination, in that any of the Lambert solutions of Gauss, Battin, Gooding, or Der could be incorporated. But for the asteroid example at hand, a Lambert solution attributable Gauss, with some modifications, is used to illustrate the method. [View Full Paper]

### AAS 14 – 289

**Convergence Behavior of Series Solutions of the Lambert Problem**

**James D. Thorne**, System Evaluation Division, Institute for Defense Analyses, Alexandria, Virginia 22311, U.S.A.

Lambert's problem, to find the unique conic trajectory that connects two points in a spherical gravity field in a given time, is represented by a set of transcendental equations due to Lagrange. The associated Lagrange equations for the orbital transfer time may be expressed as series expansions for all cases. Power series solutions have been published that reverse the functionality of the Lagrange equations to provide direct expressions for the unknown semi-major axis as an explicit function of time. The convergence behavior of the series solutions is examined over the range of possible transfer angles and flight times. The effect of arbitrary precision calculations is shown on the generation of the series coefficients. [View Full Paper]

### AAS 14 – 290

**A New Approach to Gaussian Initial Orbit Determination**

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

Gaussian IOD is based on the sector-to-triangle ratio, which incorporates the dynamical information associated with Keplerian motion, generating highly nonlinear equations. These equations are usually separated into two sets and solved iteratively in a two-level scheme. A more straightforward attack on the solution is better sought by directly solving the full system of nonlinear equations. It is shown here how a system of six equations in six unknowns can be set up using the same basic tools that characterize the Gaussian method. The six equations are actually redundant and could be easily reduced to five. However, computational and robustness considerations suggest that the symmetric looking system embodying the full Gauss approach be left untouched.
[View Full Paper]

### AAS 14 – 291

**Space-Time Coordinate Systems in the High-Precision Orbit Prediction**

**Lu Deng**, **Yinrui Rao** and **Chao Han**, School of Astronautics, Beihang University, Haidian District, Beijing, China; **Qinqin Luo**, Beijing Aerospace Technology Institute, Beijing, China

In the application of spacecraft, there are two basic coordinate systems: celestial system and terrestrial system. With the rapid development of observation techniques, the model of these two basic coordinate systems has grown increasingly accurate in recent years. How much difference are there among these coordinate systems and their corresponding transformation methods is really a problem. This paper summarized concepts and transformation methods consist with the *International Astronomical Union* (IAU) and the *International Earth Rotation Service* (IERS), applied the three common transformation methods to the prediction of four kinds of typical orbits and then compared and analyzed the results. [View Full Paper]

## AAS 14 – 292

### Initial Relative Orbit Determination Using Multiple LOS Measurements and Gaussian Mixture Models

**Keith A. LeGrand**, **Kyle J. DeMars** and **Henry J. Pernicka**, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.

The unobservability of space-based angles-only orbit determination can be mitigated by the inclusion of angle measurements from a second optical sensor fixed at a known baseline on the observing spacecraft. Previous approaches to the problem have used these stereoscopic angles to triangulate the position of a second satellite at a given time step. However, due to the nonlinearity of stereo triangulation, zero-mean Gaussian noise of these measurements cannot be assumed. This work investigates a modified approach in which the uncertainty of both angle measurements is used to bound a region for all possible positions of the second satellite. A Gaussian mixture that represents uniform uncertainty across the bounded region for the position of the second object is constructed at two initial time steps. Linkage of the Gaussian mixtures is performed using a new second-order relative Lambert solver in order to formulate a full state probability density function that can be further refined through processing subsequent measurement data in a Bayesian framework. [View Full Paper]

## AAS 14 – 293

### A Second Order Method for Initial Relative Orbit Determination Using Angles-Only Observations

**Ethan Pratt**, Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, Virginia, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.;
**Brett Newman**, Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, Virginia, U.S.A.

This paper addresses initial relative orbit determination using line-of-sight angle measurements coupled with a nonlinear motion model. An analytical solution procedure for the deputy satellite's initial Cartesian states relative to the chief satellite assuming planar motion and a circular chief orbit is investigated. A series of line-of-sight observations coupled with a closed-form second order solution for the deputy motion based on Volterra convolution theory leads to a set of nonlinear measurement equations. Relations are converted to a linear formulation with constraints, where a matrix decomposition and computation of an unknown scaling factor are required. Performance of the initial relative orbit determination procedure is evaluated with computer simulation across a large test space while varying factors such as noise level, scaling parameter technique, sample rate, and along-track drift rate. Overall, the procedure facilitates recovery of the deputy relative orbital state with requisite accuracy such that the information could be passed on to a refined precision orbit determination procedure. [View Full Paper]

**AAS 14 – 294**

**Bézier Description of Space Trajectories**

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

Bézier functions are highly versatile polynomials capable to describe complicate curves. These can be used with a Least Square approach to describe space trajectories when approximated knowledge of positions are available. This method is here applied to develop an autonomous positioning system for a spacecraft using a visible camera observing a close body (e.g., Moon, Earth) and, by image processing, estimating the vector to the body center. Acquired measurements, weighted accordingly to their accuracies, determine the control points, that are estimated by least-square method. Therefore, the estimate of the position has the undisputed advantage of being independent from both dynamics and perturbations knowledge, sometime difficult to model. Its speed and computational efficiency, make it a good candidate for on-board use. The proposed approach to estimate the position has been tested for Keplerian orbits (with various values of eccentricity) and a cislunar trajectory. The accuracy provided by the proposed method is then compared with a weighted iterative least-square and an Extended Kalman Filter. [View Full Paper]

**AAS 14 – 295**

**Orbit Determination for the Low-Thrust Spacecraft**

**Tsutomu Ichikawa**, Japan Aerospace Exploration Agency (JAXA), Sagamihara, Kanagawa, Japan

There are interplanetary mission by using continuously Low-thrust system instead of impulse thrust system. This paper is described Earth-based orbit determination capability for the low-thrust spacecraft in the light of recent developments both in a few station tracking concepts and in the thrust subsystem error modeling. Both suboptimal and optimal orbit determination performance are determined for a wide range of process noise parameter values. The tracking techniques are found to be extremely effective, reducing orbit determination errors by orders of magnitude over that obtained with conventional single-station tracking. [View Full Paper]

**AAS 14 – 296**

**(Paper Withdrawn)**

## SESSION 10: ATTITUDE DETERMINATION AND SENSORS
## Chair: Carolin Frueh, Texas A&M University

### AAS 14 – 297

### Mapping to Compensate Radial Geometrical Distortion in Pin-Hole Cameras

**Daniele Mortari**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.; **Martín E. Avendãno**, Departamento de Matemàtica Aplicada, Universidad de Zaragoza, Zaragoza, Spain.

Moon images can be used to estimate spacecraft position using a visible camera. However, even though Moon is spherical, its contour on pin-hole camera imager is, in general, slightly elliptical. This is because pin-hole cameras perform gnomonic projections, projections affected by geometrical radial distortion. This geometrical radial distortion is usually corrected by Brown's distortion model. This model corrects the radial distortion by a truncated polynomial in terms of radius. In this paper, a new global mapping approach is provided to minimize geometrical radial distortion. Motivations come from the fact that many features extracting algorithms mistakenly use direct image coordinates and do not take into account the radial distortion. The *f*-radius sphere is introduced and two mathematical approaches to remove the radial distortion are presented, for continuous ideal imager and for a real imager with finite pixel dimensions. The presented techniques are devised to better perform star centroid using von Mises-Fisher distribution and to better estimate Moon center and radius using conical sigmoid functions. [View Full Paper]

### AAS 14 – 298
### (Paper Withdrawn)

### AAS 14 – 299

### Approximate Constrained Time-Optimal Reorientation Maneuvers Using Covariance Matrix Adaptation-Evolutionary Strategy

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

The CMA-ES method is applied directly to the constrained satellite reorientation problem. This method is shown to give a very good approximate optimal solution to the constrained problem. The paper examines the performance for the constrained problem, and considers a modification that removes the eigen-decomposition step in the early stages of the iteration to achieve greater computational speed. [View Full Paper]

## AAS 14 – 300

### Gyro-Free Rigid Body Attitude Stabilization Using Only Vector Measurements on *SO*(3)

**D. Thakur** and **M. R. Akella**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas, U.S.A.

Attitude stabilization of a rigid body is considered for the case when only a set of unit vector measurements is available for control feedback. In particular, we assume that angular velocity information is either unavailable or unreliable due to faulty gyroscopes. We propose a novel control scheme for stabilizing the rigid body's orientation to the desired configuration by using unit vector measurements for feedback. That is, rather than relying on an estimated attitude vector or rate gyro measurements, the novel control law is designed to employ the unit vector measurements directly for attitude regulation. The control law is formulated on the special orthogonal group SO(3) and satisfies the so-called self-regulation property, wherein the resulting control law does not require information about the rigid-body inertia parameters. Passive systems theory and the Kalman-Yakubovich-Popov lemma are used to synthesize the control feedback. We provide detailed Lyapunov-based proofs for the convergence and stability properties of closed-loop system and present numerical simulation examples to help illustrate the technical aspects of this work. [View Full Paper]

## AAS 14 – 301

### Attitude Estimation Via Lidar Altimetry and a Particle Filter

**Brian Gaudet**, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.; **Roberto Furfaro**, Department of Systems and Industrial Engineering, Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona, U.S.A.; **Bogdan Udrea**, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.

Given a three dimensional (3D) point cloud of a resident space object (RSO) and a chaser spacecraft with a scanning LIDAR, we need to determine the relative position, velocity, attitude, and rotational velocity between the spacecraft and the RSO. For this initial work, we assume that the relative position and velocity of the chaser spacecraft are known, and use a Rao-Blackwellized particle filter to infer the relative attitude and rotational velocity of the RSO with respect to the chaser. Specifically, we assume that the relative attitude is defined as the rotations around the x, y, and z axes of the point cloud reference frame necessary to align the point cloud axes with the axes of an inertial reference frame, which in practice could be maintained with high accuracy by the chaser spacecraft attitude determination system. The angular rate is just the time derivative of these rotations determined at fixed time intervals. [View Full Paper]

**AAS 14 – 302**

**Memory Adaptive K-Vector**

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

This paper present two new capabilities of the **k**-vector range searching technique. The first one is a new feature for database with invariant number of elements whose values are changing. For these database, as long as the elements variation do not generate values outside the database bounds, the **k**-vector is updated by a very fast and computationally simple procedure with no need to rebuild the entire **k**-vector. The second new capability is the ability to build the **k**-vector with *any* size of available memory, making the **k**-vector independent from the database size. This new feature is particularly suitable on onboard space implementation where the memory available is limited as well as on ground applications when dealing with strongly nonlinear database. The more memory is available to allocate **k**-vector elements the faster the range searching is. Performance analysis for these two new enhancements and examples are provided.
[View Full Paper]

**AAS 14 – 303**

**Shape, Surface Parameter, and Attitude Profile Estimation Using a Multiple Hypothesis Unscented Kalman Filter**

**Charles J. Wetterer**, **Bobby Hunt** and **Kris Hamada**, Integrity Applications Incorporated – Pacific Defense Solutions, Kihei, Hawaii, U.S.A.; **John L. Crassidis**, Department of Mechanical & Aerospace Engineering, University at Buffalo, Amherst, New York, U.S.A.; **Paul Kervin**, Air Force Research Laboratory, Kihei, Hawaii, U.S.A.

Multiple hypothesis testing using an underlying Unscented Kalman Filter (UKF) to estimate state parameters has been previously demonstrated where the state includes the attitude, angular rate, position, velocity, and surface parameters of the space object. This algorithm is extended to include multiple components, and multiple bandpasses. An example scenario is presented where the models are proxy geostationary Earth orbit (GEO) satellites with different bus configurations (e.g. cylinder vs. rectangular prism) and in different controlled states (e.g. nadir-tracking vs. Inertial). [View Full Paper]

**AAS 14 – 304**

**(Paper Withdrawn)**

**AAS 14 – 305**

**Catalog-Free Angular Rate Estimation and On-Line Detection of Resident Space Objects**

**Brad Sease**, Aerospace & Ocean Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.; **Brien Flewelling**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.; **Yunjun Xu**, Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, Florida, U.S.A.

Star-tracker systems are typically limited by the angular rates at which they operate due to the tendency for stars to “streak” across the image plane. Due to this limitation, spacecraft relying primarily on feedback from a star-tracker system must either perform rate-limited maneuvers or rely on secondary sensor systems for the duration of the maneuver. Here, an algorithm is presented which makes use of streaked star images to provide angular rate measurements. Building on previous work which produced two attitude estimates from a single streaked star image, the algorithm detailed here removes the need for a star catalog and provides rate-only estimates. Additionally, it becomes possible to identify some non-star behavior with minimal additional processing. In this paper a simple star camera model is detailed, a stellar gyroscope algorithm is presented, and three fundamental indicators of non-star behavior are discussed. Simulation results are presented for multiple characteristic scenarios and the performance is quantified.
[View Full Paper]

### AAS 14 – 306

**Application of the Extended $H_\infty$ Filter for Attitude Determination and Gyro Calibration**

**William R. Silva** and **Hélio K. Kuga**, Space Mechanics and Control Division, National Institute for Space Research (INPE), São José dos Campos, S.P., Brazil;
**Maria C. Zanardi**, Group of Orbital Dynamics and Planetology, São Paulo University (UNESP) Guaratinguetá, S.P., Brazil

This work describes the attitude determination and the gyros drift estimation using the Extended $H_\infty$ Filter for nonlinear systems. Such filter uses the Taylor series to approximate the non-linearity of the known dynamics and assumes that the noise sources have approximately known statistical properties. The application uses measurement data of a real satellite CBERS-2 (China Brazil Earth Resources Satellite 2) which has polar sun-synchronous orbit with an altitude of 778km, crossing Equator at 10:30am in descending direction, frozen eccentricity and perigee at 90 degrees, and provides global coverage of the world every 26 days. Herein one proposes to use an extension of the $H_\infty$ linear filter for the nonlinear case of attitude estimation with nonlinearity in both the dynamics and the measurement model. The aim is to highlight and magnify the properties of the $H_\infty$ filter in terms of its favourable characteristics. Actually, the so named extended $H_\infty$ filter provides a rigorous method for dealing with systems that have model and noise uncertainties. The derivation and customization of the filter to this specific application (attitude determination) are described together with details of implementation. Besides, one preferred to use real measured DSS (Digital Solar Sensor), IRES (Infrared Earth Sensor), and gyro data to assess the procedure in a real application. The results in this work show that one can reach accuracies in attitude determination within the prescribed requirements, besides providing estimates of the gyro drifts which can be further used to enhance the gyro error model. [View Full Paper]

## AAS 14 – 307

### Bilinear Observer/Kalman Filter Identification

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

Bilinear systems are important per se since several phenomena in engineering and other fields are inherently bilinear. Even more interestingly, bilinear systems can approximate more general nonlinear systems, providing a promising approach to handle various nonlinear identification and control problems, such as satellite attitude control. This paper develops and demonstrates via numerical examples a method for discrete-time state-space model identification for bilinear systems in the presence of noise in the process and in the measurements. The formulation relies on a bilinear observer which is proven to have properties similar to the linear Kalman filter under the sole additional assumption of stationary white excitation input, and on a novel approach to system identification based on the estimation of the observer residuals. The latter are used to construct a new, noise-free identification problem, in which the observer is identified and the matrices of the system state-space model are recovered. The resulting method represents the bilinear counterpart of the Observer/Kalman filter Identification (OKID) approach for linear systems, originally developed for the identification of lightly-damped structures and distributed by NASA. [View Full Paper]

## SESSION 11: LOW-THRUST TRAJECTORY DESIGN
**Chair: Geoffrey Wawrzyniak, a.i. Solutions**

**AAS 14 – 308**
**(Paper Withdrawn)**

**AAS 14 – 309**

### Global Optimization of Low-Thrust, Multiple-Flyby Trajectories at Medium and Medium-High Fidelity

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

Global optimization of low-thrust, multiple-flyby trajectories is one of the most challenging problems in interplanetary mission design. The challenge is to develop a method that can design a complex trajectory with little or no human oversight. In the last few years several authors have developed such methods. To date each of those methods required many simplifications of the low-thrust trajectory model in order to perform a global search. In this work a global optimization framework, the Evolutionary Mission Trajectory Generator (EMTG), is presented. A medium-fidelity model based on the well-known Sims-Flanagan transcription is combined with a global optimization heuristic to generate an initial guess for a medium-high fidelity optimization using an integrated trajectory model. When combined, these two methods allow a trajectory designer to rapidly evaluate a wide range of solutions to complex problems.
[View Full Paper]

## AAS 14 – 310

### Analytical Partial Derivative Calculation of the Sims-Flanagan Transcription Match Point Constraints

**Donald H. Ellison**, Department of Aerospace Engineering, University of Illinois, Urbana Champaign, Illinois, U.S.A.; **Jacob A. Englander**, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.; **Martin T. Ozimek**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.; **Bruce A. Conway**, Department of Aerospace Engineering, University of Illinois, Urbana Champaign, Illinois, U.S.A.

The optimization of low-thrust spacecraft trajectories is a complex problem that lends itself to the use of direct method optimization techniques, rather than indirect, primarily due to their ability to converge to a feasible solution from a very poor initial guess. Many low-thrust trajectory optimizers make use of large-scale nonlinear programming packages to solve the parameter optimization problem resulting from the discrete transcription of a continuous optimal control problem. The most well-known of these tools is probably the Sparse Nonlinear OPTimizer (SNOPT). The algorithms of gradient-based optimization packages such as SNOPT's sequential quadratic programming technique rely on knowledge of the system Jacobian. While SNOPT is capable of calculating the Jacobian entries numerically using finite differencing, specifying these partial derivatives analytically results in more efficient solver performance. We present methods for the calculation of exact analytical expressions for the partial derivatives of the match point constraints of the "up-to-unit vector control" variant of the Sims-Flanagan transcription. These derivatives represent approximately 92% of the dense Jacobian entries for the Sims-Flanagan problem and their analytical specification significantly increases solver execution speed and improves solution quality.
[View Full Paper]

## AAS 14 – 311

### Automation of Multi-Revolution Low-Thrust Transfer Optimization Via Differential Evolution

**Jose M. Sánchez Pérez**, ESA/ESOC, HSO-GFA, Darmstadt, Germany;
**Andrea Campa**, CNES, Toulouse Space Centre, Toulouse, France

This paper addresses the problem of many-revolutions low-thrust transfer in the two-body problem. The optimal control for the thrust direction is formulated as a two points boundary value problem applying Pontriagyn's minimum principle. By combining averaging techniques and continuation methods the differential equations are smoothed significantly. A novel technique has been developed using the Differential Evolution algorithm to find automatically a sufficiently good initial guess to ensure the convergence of the boundary value problem. This technique has been successfully applied to several orbit transfers to solve the minimum-time problem and to obtain the Pareto front of minimum-propellant problems. [View Full Paper]

AAS 14 – 312

**Averaging Technique in T_3D an Integrated Tool for Continuous Thrust Optimal Control in Orbit Transfers**

**Thierry Dargent**, Thales Alenia Space, Cannes, France

The averaging technique introduced in T_3D optimal control tool for satellite orbit transfer enable to solve orbit transfer problems with a large number of revolutions: minimum time transfer or minimum fuel transfer can be solved easily. The proposed technique keeps the time as independent variable and do not perform the classical exchange between time and longitude. This choice has the interest to simplify the link from averaged to non-averaged dynamics, it authorizes to perform rendezvous in mean longitude and it helps to exchange solution from averaged to non-averaged problem. The time remains a physical time and not an averaged time. It can be used without error as a time to compute time dependent perturbations. It keeps the formulation generic. Different examples will show the efficiency of the method from classical transfer in a two body field but also with more sophisticated dynamics and constraints like: Third-body perturbation, Solar Radiation Pressure, Spherical Harmonics potential decomposition of the central body, atmospheric drag and motor shutdown in eclipse. [View Full Paper]

**AAS 14 – 313**
**(Paper Withdrawn)**

AAS 14 – 314

**Low-Thrust Trajectory Optimization With Gravity Assist in a Full Ephemeris Model**

**Xingshan Cai**, **Junfeng Li** and **Xiangyuan Zeng**, School of Aerospace, Tsinghua University, Beijing, China

Significant propellant mass saving can be obtained with the use of complex multiple intermediate flyby maneuvers for electric propulsion system. A two-body model can no longer satisfy the accuracy requirements in the practical engineer. This paper presents a full ephemeris model which introduces the third body's gravity, especially the GA planet's gravity, in a dynamic equation. At the same time, this paper built a set of position and velocity constraint at the perigee time relative to GA planet to guide the spacecraft fly through the sphere of influence of GA planet to get GA.
[View Full Paper]

## AAS 14 – 315

**Preliminary 2-D Optimization of Low-Thrust, Geocentric to Halo Orbit, Transfers Via 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.

Particle Swarm Optimization (PSO) is used to optimize a low-thrust trajectory from a geocentric orbit to a Lagrange point orbit in the Earth-Moon system. Unlike a gradient based approach, this evolutionary PSO algorithm is capable of avoiding undesirable local minima. The PSO method is extended to a "local" version and uses a two dimensional search space that is capable of reducing the CPU run-time by an order of magnitude when compared with published work. A technique for choosing appropriate PSO parameters is demonstrated and an example of an optimized trajectory is discussed. [View Full Paper]

## AAS 14 – 316

**(Paper Withdrawn)**

## AAS 14 – 317

**(Paper Withdrawn)**

## AAS 14 – 318

**Classifications of Time-Optimal Medium-Acceleration Interplanetary Transfers**

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

This paper presents an initial parametric study of Earth-Mars time-optimal low-thrust transfers with constant acceleration varying between $10^{-4.8}g$ and $10^{-2.5}g$. After presenting an initial approach to compute large numbers of transfers efficiently and systematically gathering them into an enumerated database, various classifications of transfers are identified and their properties explored and analyzed through the boundary conditions imposed on the problem. [View Full Paper]

## SESSION 12: ORBITAL DEBRIS
## Chair: Thomas Starchville, The Aerospace Corporation

### AAS 14 – 319

### Prediction Accuracies of Draper Semi-Analytical Satellite Theory in LEO, MEO and HEO Regime for Space Object Catalogue Maintenance

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

To ensure safe space operations, a catalogue with good ephemeris quality is required. Maintaining such a catalogue requires an accurate and precise orbit propagator that is not computationally resource consuming. Object densities in LEO, MEO and HEO regions are very high, which comprises of ~85% of the current catalogued objects. For the purpose, Draper Semi-analytical Satellite Theory (DSST) – which makes use of generalized method of averaging, is evaluated. The evaluation is carried out for the entire orbital regions in a grid fashion, instead of the traditional method of testing accuracies for test satellites. For the accuracy assessment of the selected propagator generated trajectories are compared with numerical "truth" trajectories. Computational time and RMS errors are used as comparison metrics. [View Full Paper]

### AAS 14 – 320

### Near Earth Orbit Debris Identification to Secure Future Earth-Moon Trajectory Mission

**Melissa Zemoura** and **Toshiya Hanada**, Department of Aeronautics and Astronautics, Kyushu University, Nishi-ku, Fukuoka, Japan; **Mitsunobu Okada**, ASTROSCALE PTE. LTD., International Plaza, Singapore

The proposed research aims to secure future Earth-to-Moon commercial space travels starting from year 2045. In order to achieve this objective, precise knowledge of the space environment along this transfer orbit is required. Therefore, this proposal aims to predict the debris environment of both low-Earth and geostationary orbits as it may be in the year 2045. Then, among the predicted debris population, the idea is to identify the objects potentially dangerous for the success of the mission, i.e. the objects that have a high probability to intersect the Earth-Moon transfer orbit, and to determine their origin at an earlier baseline time, set as year 2020. This identification phase is a necessary step so as to perform an effective removal process of the original objects before the generation of the identified debris, which could allow eradicating collision risks. By identifying collision risks in a relatively far future, such a proposed research could give the opportunity from now to elaborate an effective plan for debris remediation, which can be considered as an innovative aspect at a time where debris proliferation inhibition is considered as a priority by worldwide Space Agencies. [View Full Paper]

### AAS 14 – 321

**Longitude-Dependent Effects of Fragmentation Events in the Geosynchronous Orbit Regime**

**Paul V. Anderson** and **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

The effects of on-orbit fragmentation events on localized debris congestion in each of the longitude slots of the geostationary (GEO) regime are evaluated by simulating explosions and collisions of uncontrolled rocket bodies in multiple orbit configurations, including libration about one or both of the gravitational wells located at 75ºE and 105ºW. Fragmentation distributions are constructed with the NASA Standard Breakup Model, which samples the area-to-mass ratio and delta-velocity as a function of effective diameter. Simulation results indicate that the long-term severity of the fragmentation event is strongly dependent upon parent body longitude at the epoch of fragmentation, which can spawn bi-annual "debris storms" in high-risk longitude slots, driven by fragments captured by the nearby gravity well. [View Full Paper]

### AAS 14 – 322

**Characterizing Localized Debris Congestion in the Geosynchronous Orbit Regime**

**Paul V. Anderson** and **Hanspeter Schaub**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

Forecasting of localized debris congestion in the geostationary (GEO) ring is performed to investigate how frequently near-miss events occur for each of the GEO longitude slots on a daily basis, and characterize the classes of uncontrolled objects that contribute the most to macroscopic debris congestion, both globally and in a longitude-dependent sense. The present-day resident space object (RSO) population is propagated forward in time to assess congestion conditions over a 5-year time frame, and the "congestion culprits" are identified to yield recommendations for active debris removal initiatives that seek to clean-up particular longitude slots. Objects librating about one or both of the two gravitational wells located at 75ºE and 105ºW contribute 56% of the global congestion at GEO over a 5-year period, even though this object class constitutes 14% of the current GEO RSO population. [View Full Paper]

**AAS 14 – 323**

**Disposal Strategies for Spacecraft in Lagrangian Point Orbits**

**R. Armellin**, **P. Di Lizia**, **G. Di Mauro** and **M. Rasotto**, Dinamica SRL, Milano, Italy; **M. Landgraf**, European Space Agency, ESOC, Darmstadt, Germany

This work presents three different strategies for the disposal of Lagrangian Point Orbit (LPO) missions that have been analyzed in the frame of the European Space Agency study "End-of-life disposal concepts for Lagrange-points and HEO missions". The first strategy analyzes a Moon impact scenario, the second one a reentry in Earth's atmosphere, whereas the third concerns the injection into heliocentric graveyard orbits. For Moon impact and Earth's reentry an optimization problem is set up to minimize the propellant consumption while satisfying constraints on terminal position. For the graveyard, two methods are proposed: the first is a fully numerical approach based on the solution of an optimization problem via genetic algorithms, whereas the second one is based on the Jacobi constant and on a tangential disposal maneuver designed to close the Hill's regions. In this paper, solutions compatible with mission constraints are presented for SoHO and GAIA. [View Full Paper]

**AAS 14 – 324**

**Analytical Model for the Propagation of Small Debris Objects After a Fragmentation Event**

**Francesca Letizia**, **Camilla Colombo** and **Hugh G. Lewis**, Astronautics Research Group, University of Southampton, UK

Current debris evolutionary models usually neglect fragments smaller than 10 cm in their predictions because of the high computational effort they add to the simulation. However, also small fragments can be dangerous to operational satellites. This work proposes an analytical approach to describe the evolution of a cloud of small fragments generated by a collision in Low Earth Orbit. The proposed approach considers the cloud globally and derives analytically its evolution in terms of density, under the effect of drag. As a result, the analytical approach allows the representation of small fragments and noticeably reduces the computational time. [View Full Paper]

### AAS 14 – 325

**End-of-Life Earth Re-Entry for Highly Elliptical Orbits: The Integral Mission**

**Camilla Colombo**, Department Aerospace Science and Technology, Politecnico di Milano, Milano, Italy; **Francesca Letizia**, Astronautic Research Group, University of Southampton, UK; **Elisa Maria Alessi**, IFAC-CNR, Sesto Fiorentino, Italy; **Markus Landgraf**, ESA/ESOC, Darmstadt, Germany

This article presents the design of the end-of-life disposal of spacecraft in Highly Elliptical Orbits through Earth re-entry. The effect of luni-solar perturbations can be enhanced through impulsive maneuvers to move the spacecraft on a trajectory that will naturally evolve in the long-term towards an Earth re-entry. The dynamics is propagated through semi-analytical averaging techniques, implemented in the *PlanODyn* suite. Moreover, the analytical approach to describe third-body perturbation by Kozai is used to validate the solution for optimal disposal maneuvers obtained through global optimization. For INTEGRAL mission, re-entry is possible with the available $\Delta v$ onboard, provided that the orbital dynamics is wisely exploited to enhance the effects of the maneuver. [View Full Paper]

### AAS 14 – 326

**Orbital Anomaly Analysis to Detect Breakups in GEO**

**Masahiko Uetsuhara**, Institute of Statistical Mathematics, Tachikawa, Tokyo, Japan
**Toshiya Hanada**, Department of Aeronautics and Astronautics, Kyushu University, Nishi-ku, Fukuoka, Japan

This study investigates abrupt orbital changes, i.e. orbital anomalies (OAs), of the very old upper-stages Titan Transtages inserted into the geostationary orbit (GEO) region in 1960s and 1970s to find evidences of breakups. The product of the radiation pressure coefficient ($C_r$) and the area-to-mass ratio ($A/m$) are estimated by utilizing eccentricity histories of target objects separated into before-OA phase and after-OA phase. To find evidences of breakups, characteristics of likelihood distributions of $C_rA/m$ are compared between before-OAs and after-OAs. The known breakup of the Transtage 1968-081E is utilized as the reference of the comparison study. [View Full Paper]

**AAS 14 – 327**
**(Paper Withdrawn)**

**AAS 14 – 328**
**(Paper Withdrawn)**

## AAS 14 – 329

**Satellite Breakup Debris Cloud Characterization**

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

A satellite breakup caused by a hypervelocity impact or explosion will create a large number of debris particles. Eventually these particles spread 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. We provide a method to rapidly characterize the size, shape and density evolution of the cloud over time. [View Full Paper]

## SESSION 13: SPACE SITUATIONAL AWARENESS II
**Chair: Marcus Holzinger, Georgia Institute of Technology**

### AAS 14 – 331
**Collision Avoidance Maneuver Design Based on Multi-Objective Optimization**

**Alessandro Morselli**, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy; **Roberto Armellin**, School of Engineering Sciences, University of Southampton, Southampton, UK; **Pierluigi Di Lizia** and **Franco Bernelli-Zazzera**, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy

The possibility of having collision between a satellite and a space debris or another satellite is becoming frequent. The amount of propellant is directly related to a satellite's operational lifetime and revenue. Thus, collision avoidance maneuvers should be performed in the most efficient and effective manner possible. In this work the problem is formulated as a multi-objective optimization. The first objective is the $\Delta v$, whereas the second and third one are the collision probability and relative distance between the satellite and the threatening object in a given time window after the maneuver. This is to take into account that multiple conjunctions might occur in the short-term. This is particularly true for the GEO regime, where close conjunction between a pair of object can occur approximately every 12h for a few days. Thus, a CAM can in principle reduce the collision probability for one event, but significantly increase it for others. Another objective function is then added to manage mission constraint. To evaluate the objective function, the TLE are propagated with SGP4/SDP4 to the current time of the maneuver, then the $\Delta v$ is applied. This allow to compute the corresponding "modified" TLE after the maneuver and identify (in a given time window after the CAM) all the relative minima of the squared distance between the spacecraft and the approaching object, by solving a global optimization problem rigorously by means of the verified global optimizer COSY-GO. Finally the collision probability for the sieved encounters can be computed. A Multi-Objective Particle Swarm Optimizer is used to compute the set of Pareto optimal solutions.

The method has been applied to two test cases, one that considers a conjunction in GEO and another in LEO. Results show that, in particular for the GEO case, considering all the possible conjunctions after one week of the execution of a CAM can prevent the occurrence of new close encounters in the short-term. [View Full Paper]

### AAS 14 – 332
**(Paper Withdrawn)**

### AAS 14 – 333
**(Paper Withdrawn)**

## AAS 14 – 334

### Phylogenetic Taxonomy for Artificial Space Objects

**Carolin Früh** and **Moriba K. Jah**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.; **E. Valdez**, United States Geological Survey, Department of Biology, University of New Mexico, Albuquerque, New Mexico, U.S.A.; **P. Kervin**, Air Force Maui Optical & Supercomputing (AMOS), Kihei, Hawaii, U.S.A.; **T. Kelecy**, The Boeing Company, Colorado Springs, Colorado, U.S.A.

The increasing number of objects and accuracy to capture all possible characteristics, a large parameter space is utilized. In order to make the data set accessible and manageable, it is desired to reduce the parameter space to significant quantities which allow determination of differences and similarities between different objects and to group and classify them accordingly. However, the aim is not to introduce a random grouping, but to find a taxonomy of significant parameters corresponding to an actual physical and behavioral (e.g. dynamic) attributes.

In the current paper a rigorous development of a Phylogenetic system of space objects is been made in a first step, defining the framework and analogies of the system, which allows to trace back all object to their origin of creation in principle. This is the so-called a priori step. This is followed by two empirical steps: In the first step, the connection of the a priori classes and the probability of detection is shown. This is followed by the determination of hazard values for each class, which are based on the different internal energy level of each class. In the second step, a level to the taxonomy is introduced. This level is based on the orbital region of the objects. Orbital regions are determined via clustering of the orbital space of the USSTRATCOM catalog objects. In a weighted minimal tree approach combined with a modified BIRCH algorithm a grouping of the known space objects is done. [View Full Paper]

## AAS 14 – 335

### Collision Avoidance Maneuver Optimization

**Claudio Bombardelli** and **Javier Hernando Ayuso**, Space Dynamics Group, Technical University of Madrid (UPM), Madrid, Spain; **Ricardo García Pelayo**, Technical University of Madrid (UPM), Madrid, Spain

The paper presents a high accuracy fully analytical formulation to compute the miss distance and collision probability of two approaching objects following an impulsive collision avoidance maneuver. The formulation hinges on a linear relation between the applied impulse and the objects relative motion in the b-plane, which allows to formulate the maneuver optimization problem as an eigenvalue problem. The optimization criterion consists of minimizing the maneuver cost in terms of delta-V magnitude in order to either maximize collision miss distance or to minimize Gaussian collision probability. The algorithm, whose accuracy is verified in representative mission scenarios, can be employed for collision avoidance maneuver planning with reduced computational cost when compared to fully numerical algorithms. [View Full Paper]

**AAS 14 – 336**

**Parallel Construction of Ordered Binary Radix Trees for Collision Detection**

**Abel Brown**, **Michael Demoret**, **Jason Tichy** and **Ben Schilling**, a i Solutions Incorporated, Lanham, Maryland, U.S.A.

The primary purpose of Conjunction Assessment (CA) is to prevent the intersection of objects in space. Typical scenarios involve satellites intersecting with space debris or a formation of satellites with each other. As the number of objects tracked in the space debris catalogue increase each year so too the computational demands of collision detection. Traditional brute-force approaches perform an all-to-all collision search by comparing each objects relative separation to every other object. Unfortunately, such brute-force tactics scale poorly as $\mathcal{O}(N^2)$ and are thus not appropriate for real-time operational scenarios or Monte Carlo simulations involving many objects. In this paper we explore bounding volume hierarchies and present a massively parallel GPU implementation of Ordered Binary Radix Trees capable of collision detection for millions of objects in real-time. [View Full Paper]

**AAS 14 – 337**
**(Paper Withdrawn)**

**AAS 14 – 338**
**(Paper Withdrawn)**

**AAS 14 – 339**

**Photometric Data From Non-Resolved Objects for Space Object Characterization**

**Richard Linares** and **Michael Shoemaker**, Space Science and Applications, ISR-1, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.;
**David M. Palmer** and **David C. Thompson**, Space and Remote Sensing, ISR-2, Los Alamos National Laboratory, Los Alamos, New Mexico; **Josef Koller**, Space Science and Applications, ISR-1, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

This paper uses light curve measurements to estimate the attitude and angular velocities of space objects with known shape. This paper focuses on rocket bodies in particular. A nonlinear least squares estimator is used to estimate the attitude and angular velocity of the space objects; both real data and simulated data scenarios are shown. A number of representative rocket body models are used for simulated data and real data examples. Good performance was shown for both simulated and real data cases.
[View Full Paper]

**AAS 14 – 340**
**(Paper Withdrawn)**

## SESSION 14: ESTIMATION
## Chair: Kohei Fujimoto, Texas A&M University

**AAS 14 – 342**
**(Paper Withdrawn)**

**AAS 14 – 343**
### Coordinatization Effects on Non-Gaussian Uncertainty for Track Initialization and Refinement

**James S. McCabe** and **Kyle J. DeMars**, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.

A comparison between common coordinate systems used for state representation in orbital mechanics is presented for track initialization in orbit determination and follow-on tracking utilizing optical angles-only measurements. A Gaussian mixture parameterized probability density function representing uniform uncertainty across all possible Earth-bound constrained orbits is constructed. This distribution is mapped into each coordinate system, propagated forward in time, and refined via a Bayesian filter. Performance measures related to uncertainty characterization are applied to judge the efficacy of the method in each coordinate system. [View Full Paper]

**AAS 14 – 344**
### An Automatic Domain Splitting Technique to Propagate Uncertainties in Highly Nonlinear Orbital Dynamics

**Alexander Wittig** and **Pierluigi Di Lizia**, Department of Aerospace Science and Technology, Politecnico di Milano, Milano, Italy; **Roberto Armellin**, School of Engineering Sciences, University of Southampton, Southampton, UK; **Franco Bernelli Zazzera**, Department of Aerospace Science and Technology, Politecnico di Milano, Milano, Italy; **Kyoko Makino** and **Martin Berz**, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, U.S.A.

Current approaches to uncertainty propagation in astrodynamics mainly refer to linearized models or Monte Carlo simulations. Naive linear methods fail in nonlinear dynamics, whereas Monte Carlo simulations tend to be computationally intensive. Differential algebra has already proven to be an efficient compromise by replacing thousands of pointwise integrations of Monte Carlo runs with the fast evaluation of the arbitrary order Taylor expansion of the flow of the dynamics. However, the current implementation of the DA-based high-order uncertainty propagator fails in highly nonlinear dynamics or long term propagation. We solve this issue by introducing automatic domain splitting. During propagation, the polynomial of the current state is split in two polynomials when its accuracy reaches a given threshold. The resulting polynomials accurately track uncertainties, even in highly nonlinear dynamics. The method is tested on the propagation of (99942) Apophis post-encounter motion. [View Full Paper]

### AAS 14 – 345

**Adaptable Iterative and Recursive Kalman Filter Schemes**

**Renato Zanetti**, Autonomous Flight Systems, NASA Johnson Space Center, Houston, Texas, U.S.A.

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) and, to a much lesser extent, the unscented Kalman filter. The Iterated Kalman filter (IKF) and the Recursive Update Filter (RUF) are two algorithms that reduce the consequences of the linearization assumption of the EKF by performing $N$ updates for each new measurement, where $N$ is the number of recursions, a tuning parameter. This paper introduces an adaptable RUF algorithm to calculate $N$ on the go, a similar technique can be used for the IKF as well.
[View Full Paper]

### AAS 14 – 346

**Error Estimation and Control for Efficient and Reliable Orbit (and Uncertainty) Propagation**

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

Several promising implicit-Runge-Kutta-based methods for orbit propagation have been developed in recent years. This paper elaborates on some of the unique features of the authors' variable-step implementation of Gauss-Legendre implicit Runge-Kutta (GL-IRK), including (i) the ability to collectively, rather than individually, propagate nearby orbits that arise in the context of uncertainty propagation, and (ii) the use of error estimation and control methods from numerical analysis for improved efficiency and reliability. Such benefits are quantified by comparing the performance of a variable-step implementation of GL-IRK to that of a fixed-step implementation. Difficulties associated with the use of fixed-step or pseudo-adaptive methods for orbit propagation are also discussed. [View Full Paper]

**AAS 14 – 347**

**Orbital Density Determination From Unassociated Observations: Uninformative Prior and Initial Observation**

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

Unassociated partial-state observations of orbits can provide probabilistic information on the built orbital environment, though traditionally astrodynamicists attempt no analysis of observations until they've been associated. With a large population of small (< 10 cm) objects that could be detected with modern sensors but would still remain unassociated, this is potentially good information that is being ignored. All velocities, within physically defined limits, may be assumed to be equally probable for an observation of an object with position only, and the two together provide complete state information. Orbits can be identified and observations probabilistically associated from an ensemble of unassociated observations from different objects. Such a technique would be an important component of using non-tracking sensors and analysis to compose a time evolution of density in orbit space rather than the traditional approach of composing a histogram of only those objects large and important enough to be tracked and cataloged. [View Full Paper]

**AAS 14 – 348**
**(Paper Withdrawn)**

**AAS 14 – 349**

**Drag Coefficient Estimation Using Satellite Attitude and Orbit Data**

**Christopher L. Hassa** and **David B. Spencer**, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.;
**Sven G. Bilén**, Department of Engineering Design, Electrical Engineering, and Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.

Current spacecraft decay models assume a constant value of 2.2 for the coefficient of drag. This assumption is driven by the difficulty in accurately modeling the spacecraft's cross-sectional area exposed to the direction of motion. This research discards the assumption of a constant coefficient of drag; instead, it uses attitude data from the *Swift* spacecraft to determine the cross-sectional area and directly calculates the coefficient of drag over the nine years of orbital data. This method partially validates the NRLMSISE-00 atmospheric model and encourages a new examination of the coefficient of drag value used to determine the decay of spacecraft orbits. [View Full Paper]

**AAS 14 – 350**
**(Paper Withdrawn)**

**AAS 14 – 351**

**Estimation and Prediction for an Orbital Propagation Model Using Data Assimilation**

**Humberto C. Godinez**, Applied Mathematics and Plasma Physics, Los Alamos National Laboratory, Los Alamos New Mexico, U.S.A.; **Matthias Morzfeld**, Department of Mathematics, University of California, Berkeley, California, U.S.A., and Lawrence Berkeley National Laboratory, Berkeley, California, U.S.A.

Accurate tracking and prediction of the position and velocity of an orbiting object, e.g. Of a (defunct) satellite, is an important capability to keep the space infrastructure safe. In this work, the orbital determination problem is solved via Bayesian statistics: a numerical model of an orbiting object (called an orbital propagation model) is frequently updated with data, i.e. noisy measurements of the object's state; this process is called data assimilation in geophysics. Since orbital dynamics are non-linear, the probability distributions one encounters in data assimilation are non-Gaussian. This can cause problems in methods that rely on linear/Gaussian approximations, e.g. the ensemble Kalman filter (EnKF). A series of extensive numerical experiments are performed to test and compare linear as well as non-linear data assimilation strategies in the context of orbital determination. In particular, EnKF and Monte Carlo (MC) sampling are applied to a two-dimensional orbital estimation problem. The experiments indicate that EnKF can potentially perform poorly because of the strong non-linear effects, while the MC sampling can perform well and at a reasonable computational cost.

[View Full Paper]

## SESSION 15: SMALL BODY PROXIMITY OPERATIONS
### Chair: Chris Ranieri, The Aerospace Corporation

### AAS 14 – 352

**Body-Fixed Orbit-Attitude Hovering at Equilibria Near an Asteroid Using Non-Canonical Hamiltonian Structure**

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

Orbit-attitude hovering of a spacecraft at the natural relative equilibria in the body-fixed frame of a uniformly rotating asteroid is discussed in the framework of the full spacecraft dynamics, in which the spacecraft is modeled as a rigid body with the gravitational orbit-attitude coupling. In this hovering model, both the position and attitude of the spacecraft are kept to be stationary in the asteroid body-fixed frame. A Hamiltonian structure-based feedback control law is proposed to stabilize the relative equilibria of the full dynamics to achieve the orbit attitude hovering. The control law is consisted of two parts: potential shaping and energy dissipation. The potential shaping is to make the relative equilibrium a minimum of the modified Hamiltonian on the invariant manifold by modifying the potential artificially. With the energy-Casimir method, it is shown that the unstable relative equilibrium can always be stabilized in the Lyapunov sense by the potential shaping with sufficiently large feedback gains. Then the energy dissipation leads the motion to converge asymptotically to the minimum of the modified Hamiltonian on the invariant manifold, i.e., the relative equilibrium. The feasibility of the proposed stabilization control law is validated through numerical simulations in the case of a spacecraft orbiting around a small asteroid. The main advantage of the proposed hovering control law is that it is very simple and is easy to implement autonomously by the spacecraft with little computation. This advantage is attributed to the utilization of dynamical behaviors of the system in the control design.
[View Full Paper]

### AAS 14 – 353

**Solar Sailing Apophis Rendezvous Mission With Fuel-Fixed Delta-V**

**Xiangyuan Zeng**, **Jing He**, **Junfeng Li**, **Shengping Gong**, **Xingshan Cai** and **Zhiguo Zhang**, School of Aerospace, Tsinghua University, Beijing, China

The subject of this paper is the trajectory design and optimization for Apophis rendezvous missions by using solar sailing. An ideally reflective sail model is utilized in the two body dynamic equations. Hyperbolic excess velocities at the departure and rendezvous points are considered with a fixed maximum magnitude. The time optimal control problem is solved by using an indirect method yielding a two point boundary value problem. Numerical examples and discussions are presented for a near term realistic solar sail in a characteristic acceleration of 1 mm/s$^2$. The highest impulsive velocity is no more than 5 km/s. The effect of departure excess velocities, arrival velocities and their combinations are investigated in a parametric way. The time optimal trajectories are studied with different impulsive velocities with launch windows after January 1, 2013 in a synodic period of the Earth and Apophis. [View Full Paper]

## AAS 14 – 354

### Asteroid Proximity Navigation Using Direct Altimetry Measurements

**Jay W. McMahon** and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **Kevin Berry**, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

This paper examines the efficacy and limits of using only altimetry measurements for on-board orbit determination in close proximity to an asteroid. This is a challenging problem for several reasons. First, inferring the spacecraft position from an altimetry measurement requires a detailed model of the asteroid's topography. Second, even if the asteroid shape is known perfectly, a single range measurement only provides information on the component of the spacecraft position along the direction measured. Thus multiple measurements in different directions and/or at different times are required for full observability. Therefore, this paper focuses on understanding what information can be extracted from altimetry measurements for navigation, how useful this information is for estimating the spacecraft state, and how these measurements can be successfully processed, especially with regard to unknown topography. Special attention is given to understanding how to pick the best set of a finite number of measurements to give the most robust estimate of the spacecraft state. The results of this study demonstrate how a set of altimetry measurements can be used for orbit determination in close proximity of an asteroid, and most importantly the degree of accuracy that can be expected with such a method for a finite number of measurements. [View Full Paper]

## AAS 14 – 355

### High-Altitude Deployment of Landers to Asteroid Surfaces Using Natural Manifolds

**Simon Tardivel** and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.;
**Patrick Michel**, University of Nice-Sophia Antipolis, CNRS, Nice, France

A simple, reliable and safe strategy for deploying landers to any asteroid surface is described. The deploying spacecraft cruises on a slow hyperbolic trajectory and releases a landing pod, devoid of any guidance, navigation and control system or actuators, from very high altitude above the asteroid, near saddle points of the amended gravity field. At release, the spacecraft gives the lander initial conditions such that the dynamical environment of the asteroid naturally leads the pod to the surface. The deployment region and favorable initial conditions are computed and discussed. Monte Carlo simulations verify the efficacy and the robustness of the presented strategy. [View Full Paper]

## AAS 14 – 356

### Trajectory Design About Binary Asteroids Through Coupled Three-Body Problems

**Fabio Ferrari** and **Michèle Lavagna**, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy; **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

The study of the dynamical environment near an asteroid pair has become an extremely relevant topic to design trajectories for future missions design. This study analyzes the dynamical environment in the proximity of a binary asteroid system and develops some useful tools to design trajectories about the asteroid couple, exploiting convenient dynamical properties of three-body systems. The interaction between two different three-body systems is analyzed and a convenient dynamical environment is defined in the vicinity of the asteroid pair by introducing the concept of Surface Of Equivalence (SOE). A possible trajectory design method is shown, using invariant manifolds associated to the Circular Restricted Three-Body Problem and multi-dimensional Poincaré maps. An example of a suitable trajectory for the lift-off/landing of a spacecraft from the primary asteroid is finally shown. [View Full Paper]

## AAS 14 – 357

### Rosetta Lander Philae Mission: Flight Dynamics Studies for Landing Site Selection on Comet Churyumov–Gerasimenko

**Eric Jurado**, **Alejandro Blazquez**, **Thierry Martin** and **Elisabet Canalias**, Centre National d'Etudes Spatiales (CNES), Toulouse, France; **Romain Garmier** and **Thierry Ceolin**, CS-SI Toulouse, France; **Jens Biele**, DLR Cologne, Germany; **Koen Geurts**, DLR Cologne / Telespazio VEGA Deutschland GmbH Darmstadt, Germany

In August 2014, the European mission Rosetta will reach its target comet Churyumov-Gerasimenko. After several months characterizing the comet thanks to remote observations, it will deliver the Philae Lander on the comet nucleus surface in November 2014. The data collected with the Orbiter instruments observation will be used to choose the Philae Landing Site. This paper addresses Flight Dynamics analyses carried out in the scope of the Landing Site Selection Process, and preparation of landing. Different separation and descent scenarios are studied to maximize the reachable areas on the nucleus, taking into account the constraints linked to Lander and Orbiter vehicles design. It is necessary to bear in mind that today the comet environment is hardly known, and that the comet models used for these studies may be far from reality. Analyses will be refined during the last months before landing using comet observation data. After landing, it will also be necessary to determine within a few hours where and how Philae has landed. Technical solutions for estimating the location and the orientation of the Lander once landed are presented in this paper. [View Full Paper]

**AAS 14 – 358**
**(Paper Withdrawn)**

**AAS 14 – 359**
**ZEM/ZEV Sliding Guidance for Asteroid Close-Proximity Orbital Transfer and Rendezvous**

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

The Zero-Effort-Miss/Zero-Effort-Velocity (ZEM/ZEV) with sliding mode guidance scheme is applied to the problem of asteroid proximity-operations orbit transfer and rendezvous. This guidance scheme is a non-linear methodology which combines techniques from both optimal and sliding control theories to generate a guidance framework which generates a thrust command based purely on the current estimated spacecraft state and desired final target state. The guidance algorithm has its roots in the generalized ZEM/ZEV feedback guidance and its mathematical equations are naturally derived by defining a non-linear sliding surface as a function of the terms Zero-Effort-Miss and Zero-Effort-Velocity. With the addition of this sliding mode augmentation, one can formally prove that the developed guidance law is globally stable to unknown, but bounded perturbations. In this paper, the focus is the application of the guidance law to typical scenarios that can be encountered during the close-proximity operations phases of a robotic mission to a small asteroid. First, the problem of orbit transfer is analyzed and simulations are executed to determine the performance in such a scenario. Secondly, the problem of orbital rendezvous is assessed and analyzed and the performance of the guidance is again discussed. Results demonstrate that the algorithm performs well even in a largely uncertain environment and features high accuracy in the execution of such maneuvers. [View Full Paper]

**AAS 14 – 360**
**Orbital Evolution and Environmental Analysis Around Asteroid 2008 EV5**

**Pedro J. Llanos**, AstroNet-II-Astrodynamics Network, Madrid, Spain;
**James K. Miller**, Navigation Consultant, Los Angeles, California, U.S.A.;
**Gerald R. Hintz**, Astronautical Engineering Department, University of Southern California, Los Angeles, California, U.S.A.

The orbital evolution and environmental analyses around the target asteroid, 2008 EV5, for the ESA's Marco Polo R mission are assessed during the proximity operations to minimize the efforts towards the improvement of the Guidance, Navigation and Control system. With this analysis, we will extend our knowledge in the decision-making when the spacecraft is flying under unknown environmental conditions, such as the solar radiation pressure and the gravitational harmonics due to the irregular shape of the body. We compare analyses performed on different asteroid shape models, such as a parameterized model, an ellipsoid model and a high fidelity mascons shape model.
[View Full Paper]

**AAS 14 – 361**

**Heliotropic Orbits at Oblate Asteroids: Balancing Solar Pressure and J2 Perturbations**

**Demyan Lantukh** and **Ryan P. Russell**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas, U.S.A.;
**Stephen Broschart**, Mission Design and Navigation Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The combined effect of significant solar radiation pressure and body oblateness on spacecraft orbits is investigated using both singly and doubly averaged disturbing potentials with the Lagrange Planetary Equations. This combination of perturbations has applications for potential spacecraft missions to a select class of primitive bodies. A stable heliotropic equatorial family of orbits is applied in the current study to the environment near oblate asteroids. This heliotropic family along with new orbit families are identified, analyzed, and extended out of the equatorial plane. Dynamic bounds for the inclined heliotropic orbits are determined. The resulting orbits provide useful options for low-altitude science orbits around some small bodies like Bennu, the target for the OSIRIS-REx mission. [View Full Paper]

**AAS 14 – 362**
**(Paper Withdrawn)**

## SESSION 16: TRAJECTORY DESIGN II
## Chair: Ryan Russell, University of Texas at Austin

### AAS 14 – 363

**2016 Mars Insight Mission Design and Navigation**

**Fernando Abilleira**, **Ray Frauenholz**, **Ken Fujii**, **Mark Wallace** and **Tung-Han You**, InSight Mission, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Scheduled for a launch in the 2016 Earth to Mars opportunity, the Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) Mission will arrive to Mars in late September 2016 with the primary objective of placing a science lander on the surface of the Red Planet followed by the deployment of two science instruments to investigate the fundamental processes of terrestrial planet formation and evolution. In order to achieve a successful landing, the InSight Project has selected a launch/arrival strategy that satisfies the following key and driving requirements: (1) Deliver a total launch mass of 727 kg, (2) target a nominal landing site with a cumulative ΔV99 less than 30 m/s, and (3) approach EDL with a V-infinity upper limit of 3.941 km/s and (4) an entry flight-path angle (EFPA) of –12.5 ± 0.26 deg, 3-sigma; the InSight trajectories have been designed such that they (5) provide UHF-band communications via Direct-To-Earth and MRO from Entry through landing plus 60 s, (6) with injection aimpoints biased away from Mars such that the probability of the launch vehicle upper stage impacting Mars is less than $1.0 \times 10^{-4}$ for fifty years after launch, and (7) non-nominal impact probabilities due to failure during the Cruise phase less than $1.0 \times 10^{-2}$. [View Full Paper]

### AAS 14 – 364

**Robotic Mars Exploration Trajectories Using Hall Thrusters**

**Theresa D. Kowalkowski**, **Zachary J. Bailey**, **Robert E. Lock**, **Erick J. Sturm** and **Ryan C. Woolley**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

A variety of Mars exploration architectures for the latter part of this decade and early part of the next are under consideration at NASA, ranging from orbiters to landers to sample return mission scenarios. The use of solar electric propulsion, particularly Hall thrusters, is an attractive option because it can provide increased flexibility to mass growth; alternate launch opportunities; Mars orbit selection, adjustment and rendezvous capabilities; and uncertainty in launch vehicle performance. In this paper, we present Earth-to-Mars and Mars-to-Earth trajectory options using Hall thrusters for potential Mars exploration architectures. [View Full Paper]

## AAS 14 – 365

### Round-Trip Solar Electric Propulsion Missions for Mars Sample Return

**Zachary J. Bailey**, **Erick J. Sturm**, **Theresa D. Kowalkowski**, **Robert E. Lock**, **Ryan C. Woolley** and **Austin K. Nicholas**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Mars Sample Return (MSR) missions could benefit from the high specific impulse of Solar Electric Propulsion (SEP) to achieve lower launch masses than with chemical propulsion. SEP presents formulation challenges due to the coupled nature of launch vehicle performance, propulsion system, power system, and mission timeline. This paper describes a SEP orbiter-sizing tool, which models spacecraft mass & timeline in conjunction with low thrust round-trip Earth-Mars trajectories, and presents selected concept designs. A variety of system designs are possible for SEP MSR orbiters, with large dry mass allocations, similar round-trip durations to chemical orbiters, and reduced design variability between opportunities. [View Full Paper]

## AAS 14 – 366

### Preliminary Mission Design for a Crewed Earth-Mars Flyby Mission Using Solar Electric Propulsion (SEP)

**Stijn De Smet**, Delft University of Technology, Delft, The Netherlands;
**Jeffrey S. Parker** and **Jonathan F. C. Herman**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.; **Ron Noomen**, Delft University of Technology, Delft, The Netherlands

This paper discusses the preliminary design of a crewed mission to fly by Mars and return within 501 days using solar electric propulsion (SEP). The research demonstrates that new launch windows can be opened that would have been impossible to achieve using conventional chemical propulsion with a reasonable payload and present launch vehicles. Furthermore, this paper will also investigate to what extent applying SEP can minimize the launch mass or the re-entry velocity. SEP systems are considered that use anything from 10 to 25 kW of power. [View Full Paper]

**AAS 14 – 367**

**Spacecraft Trajectory Design With Photonic Laser Propulsion in the Two-Body Problems**

**Shih-Hao Liu** and **Fu-Yuen Hsiao**, Department of Aerospace Engineering, Tamkang University, Tamsui, Taiwan, R.O.C.

This paper studies the trajectory design of spacecraft propelled by the photonic laser propulsion (PLP) system under the environment of two-body problem. The PLP system is an innovative technology, and generate continuous and tremendous power by consuming very small energy with repeated reflections of laser beam. Since 2011 trajectory characteristics has been investigated by Hsiao, but trajectory design was still not studied. This paper mainly focuses on the trajectory design. Trajectory design is often modeled as a two-point boundary value problem (2PBVP). However, conventional 2PBVPs may not be suitable for this problem due to certain constraints. In this paper an algorithm is proposed to determine initial conditions in the trajectory design. Theorem of contraction mapping is employed to developed the algorithm of initial-condition determination. Numerical simulations are presented to demonstrate the algorithm and potential applications. [View Full Paper]

**AAS 14 – 368**

**There And Back Again: Using Planet-Based Sep Tugs To Repeatably Aid Interplanetary Payloads**

**Timothy P. McElrath**, Mission Design & Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.;
**John O. Elliott**, Planetary Mission Formulation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Tugs using Solar Electric Propulsion (SEP) can efficiently operate between planetary and heliocentric orbits, by delivering payloads on trajectories to planetary flybys that lead to ballistic transfers between planets, while allowing the tug to recapture at the base planet. By restricting the solar operating range, the tug power level and other spacecraft parameters can be optimized. The very long lifetime of modern Hall thrusters can be fully utilized by launching payloads, together with the xenon needed to propel them, into elliptical orbits. An Earth-based tug can use this technique every Earth-Mars synodic period, possibly in combination with a Mars-based tug operating on a two-synodic period cycle, and it can also be used for payloads to other destinations (particularly in the inner solar system), providing a significant performance improvement over direct launches. [View Full Paper]

### AAS 14 – 369

**Orbit Design and Navigation Through the End of MESSENGER's Extended Mission at Mercury**

**James V. McAdams**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.; **Christopher G. Bryan**, Space Navigation and Flight Dynamics, KinetX Aerospace, Simi Valley, California, U.S.A.; **Dawn P. Moessner**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.; **Brian R. Page** and **Dale R. Stanbridge**, Space Navigation and Flight Dynamics, KinetX Aerospace, Tempe, Arizona, U.S.A.; **Kenneth E. Williams**, Space Navigation and Flight Dynamics, KinetX Aerospace, Simi Valley, California, U.S.A.;

MESSENGER became the first orbiter of Mercury on 18 March 2011 and spent one year in a near-polar, 12-h orbit with six orbit-correction maneuvers (OCMs) to keep periapsis altitude between 200 and 500 km and maintain orbit period. MESSENGER's first extended mission, which included two mid-April 2012 OCMs that lowered the orbit period to 8 h, lasted until 17 March 2013. MESSENGER's second extended mission began on 18 March 2013, included observations of comets Encke and ISON during the fall of 2013, and will include four OCMs to target periods with little variation from 25-km and 15-km periapsis altitude until Mercury impact in March 2015.
[View Full Paper]

### AAS 14 – 370

**Mission Analysis Update for the Jupiter Icy Moon Explorer (JUICE)**

**Arnaud Boutonnet** and **Johannes Schoenmaekers**, HSO-GFA, ESA-ESOC, Darmstadt, Germany; **Waldemar Martens**, HSO-GFA, CGI at ESA-ESOC, Darmstadt, Germany; **Tomohiro Yamaguchi**, HSO-GFA, GMV at ESA-ESOC, Darmstadt, Germany

This paper presents the mission analysis update for JUICE, an ESA mission to study Jupiter, its environment and its Galilean moons. The various phases of the tour are quickly recalled (Europa swing-bys, Jupiter high latitudes, low energy endgame, Ganymede in-orbit). The interplanetary phase was updated: extended launch date interval, increased list of planets sequences, enhanced trajectory structure. The navigation of the Jupiter tour is also shown with careful attention to Jupiter capture. Finally the planetary protection analysis is presented for Europa through two contributions: short term failure (e.g. safe mode) and long term failure (e.g. micrometeoroids) in Europa crossing orbit. [View Full Paper]

## AAS 14 – 371

### Precise Determination of the Reachable Domain for a Spacecraft With a Single Impulse

**Changxuan Wen**, **Zengwen Xu**, **Yushan Zhao** and **Peng Shi**, School of Astronautics, Beihang University, HaiDian District, Beijing, People's Republic of China

Reachable Domain (RD) refers to the collection of all accessible positions for spacecraft given an initial orbit and a fuel constraint. In this paper, the fuel constraint is conveniently expressed by a single available velocity impulse. To solve the RD, the radius of an accessible target position in a given direction is formulated. Then, by evaluating the extreme values of the accessible radius in the given direction, two reachable boundaries and a reachable line segment can be solved. The RD in the three-dimensional space can be determined by rotating the direction and tracing all the reachable boundaries. The proposed method successfully gives the accurate solutions of the RD for the remaining two unresolved scenarios, namely, RD with arbitrary maneuver point and arbitrary impulse direction and RD with arbitrary maneuver point and fixed impulse direction. Numerical simulations, upon comparison with the results of the existing method, demonstrate the proposed method and its accuracy. [View Full Paper]

## AAS 14 – 372

### Europa Lander Mission Analysis: Non-Keplerian Approach for Radiation Exposure Mitigation

**Lorenzo Ferrario** and **Michèle Lavagna**, Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, Milano, Italy

According to recent analyses, Europa has been identified as one of the most promising candidates as a life-hosting celestial body thanks to the presence of a vast and oxygenated underground ocean. Many mission analyses have been designed to reach that moon, but none really mitigates the exposition to the harsh and radioactive environment of the inner Jovian magnetosphere. This paper shows how it is possible to reduce significantly that risk by exploiting a non-Keplerian trajectory based on two nested Circular Restricted 3 Bodies Problems with Ganymede and Europa, also increasing the flexibility of the mission. [View Full Paper]

## AAS 14 – 373

**Techniques For Designing Many-Revolution, Electric-Propulsion Trajectories**

**Anastassios E. Petropoulos**, **Zahi B. Tarzi** and **Gregory Lantoine**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.; **Thierry Dargent**, Thales Alenia Space, Cannes, France; **Richard Epenoy**, Centre National d'Etudes Spatiales, Toulouse, France

Many-revolution, electric-propulsion trajectories are computationally difficult to optimize. We present several examples of the well-known technique of orbit averaging coupled with indirect optimization methods, and also an example of a direct, unaveraged optimization method. We also present a comparison of these methods to the Q-law, a Lyapunov feedback control algorithm for spiral transfers. A wide variety of transfers, some involving large changes in many of the orbit elements, are analyzed to assess the strengths of the methods. [View Full Paper]

## SESSION 17: RENDEZVOUS AND PROXIMITY OPERATIONS II
**Chair: Roberto Furfaro, University of Arizona**

## AAS 14 – 374

**Solution of Lambert's Problem for Higher-Order Satellite Relative Motion**

**Keith A. LeGrand** and **Kyle J. DeMars**, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, Missouri, U.S.A.

In classical orbital mechanics, the Lambert problem consists of computing the full state of an orbiting body given two positions and the time elapsed between them. Similar analytic methods exist for the relative motion problem, but rely on linearized equations of motion and matrix inversion. In this work, an analytic solution to the "relative" Lambert problem is derived using second-order Clohessy-Wiltshire equations and is applied directly in the relative frame. The problem is represented geometrically by the intersection of three quadric surfaces. The associated multivariate algebraic set is solved non-iteratively using Macaulay resultant expressions to high accuracy.
[View Full Paper]

## AAS 14 – 375

### An Error Analysis for Relative Satellite Motion in Earth Orbit

**Jerel B. Nielsen** and **David K. Geller**, Mechanical and Aerospace Engineering Department, Utah State University, Logan, Utah, U.S.A.;
**T. Alan Lovell**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

Relative acceleration as a function of deputy distance from chief is investigated. This acceleration is computed only for LEO (7000 km) and GEO (42000 km) orbits, where the GEO orbits have an inclination of zero. Error in the CW equations is also investigated. Errors due to CW approximations and relative accelerations due to a point-mass gravity model, J2, SRP, and 3rd-body perturbations are compared and plotted as a function of radial, cross-track, and along-track position. [View Full Paper]

## AAS 14 – 376

### Rendezvous and Proximity Operations at the Earth-Moon L2 Lagrange Point: Navigation Analysis for Preliminary Trajectory Design

**Kuljit Mand**, Department of Mechanical Engineering and Materials Science, Rice University, Houston, Texas, U.S.A.; **David Woffinden**, Charles Stark Draper Laboratory, Houston, Texas, U.S.A.; **Pol Spanos**, Department of Mechanical Engineering and Materials Science, Rice University, Houston, Texas, U.S.A.;
**Renato Zanetti**, Charles Stark Draper Laboratory, Houston, Texas, U.S.A.

The Earth-Moon L2 point has attracted considerable attention as a potential location for future missions that enable spacecraft to explore beyond the far-side of the Moon and other deep space celestial bodies. The capability to rendezvous and dock is required for multiple mission objectives. A critical element associated with the trajectory design is determining the navigation requirements, which are indirectly affected by operating in this new environment.

Three preliminary trajectory designs are proposed that employ a newly developed relative targeting algorithm that accounts for multi-body affects at L2. The trajectory designs range from replicating traditional rendezvous profiles to introducing strategies that capitalize on the unique relative motion at L2. Navigation requirements necessary for rendezvous and docking at L2 are then derived and validated for each trajectory. These requirements are subsequently utilized for a sensor suite analysis to identify an optimal sensor suite for each trajectory within a quick and automated framework.
[View Full Paper]

## AAS 14 – 377

### Hovering Formation Design and Control Based on Relative Orbit Elements

**Yinrui Rao**, School of Astronautics, Beihang University, HaiDian District, Beijing, China; **Jianfeng Yin,** China Academy of Space Technology (CAST), Fengtai District, Beijing, China; **Chao Han**, School of Astronautics, Beihang University, HaiDian District, Beijing, China

A new set of relative orbit elements (ROE) is used for hovering formation design. A new impulsive control strategy for hovering formation along-track direction movement is proposed, and it has advantages of concise form and convenient implementation in engineering. Furthermore, to control the formation from any configuration to the designated hovering formation, a new strategy based on Lambert's Problem is established. Additionally, considering the impact of measurement errors and perturbations, a closed-loop impulsive feedback control law is derived as well. Several numerical simulations are presented to demonstrate the effectiveness of these proposed methods.
[View Full Paper]

## AAS 14 – 378

### Touchless Electrostatic Three-Dimensional Detumbling of Large GEO Debris

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

Touchless detumbling of space debris is investigated to enable orbital servicing or active debris removal. Using active charge transfer between a tug and debris object, control torques are created to reduce the debris spin rate prior to making any physical contact. In this work, the tug shape is spherical and the debris is assumed to be cylindrical and tumbling. The attitude control goal is to arrest the debris tumbling motion while maintaining a fixed position ahead of the GEO debris object. Prior work has identified the feasibility of electrostatic detumble for one degree of rotational freedom. This work extends the theory to three-dimensional tumbling motion. Using the previously developed Multi-Sphere modeling method for electrostatic forces and torques on non-spherical objects, Lyapunov control theory and numerical simulations are used to demonstrate a stabilizing attitude control. [View Full Paper]

## AAS 14 – 379

### State Transition Matrix for Relative Motion Including $J_2$ and Third-Body Perturbations

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

The paper extends the fidelity of the Gim-Alfriend State Transition Matrix (GA STM) by incorporating the effects of third-body gravitational perturbations. A doubly-averaged lunar potential, accounting for the lunar orbit's inclination and eccentricity, is adopted to obtain the secular rates for the orbital elements. The state vector of the Moon with respect to the Earth is obtained from ephemerides data. Consistent initial conditions for the averaged model are determined by a least squares method. The results for an example involving a reference orbit of high eccentricity show that the accuracy of the GA STM is significantly improved by the inclusion of the lunar perturbation model. [View Full Paper]

## AAS 14 – 380

### Spacecraft Swarm Finite-Thrust Cooperative Control for Common Orbit Convergence

**D. Thakur**, **S. Hernandez** and **M. R. Akella**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas, U.S.A.

A novel decentralized cooperative control protocol is proposed for the convergence of an autonomous spacecraft swarm to a common circular orbit using finite thrust. Guidance and consensus algorithms are implemented to drive agents to an orbit of prescribed semi-major axis and zero eccentricity, with the plane of orbital motion determined through consensus. The information network is assumed to be connected, undirected, and either acyclic or purely cyclic. The thrust limited guidance and consensus schemes are designed separately and readily combined for overall closed-loop stability. The convergence properties are rigorously analyzed and simulations are provided to validate results. [View Full Paper]

### AAS 14 – 381

**Relative Orbit Determination for Formation Flying Spacecraft Using Differenced Beidou Carrier Phase**

**Shu Leizheng**, **Chen Pei**, **Zhang Hongli** and **Han Chao**, School of Astronautics, Beihang University, HaiDian District, Beijing, China

A reduced-dynamic approach is developed for precise formation flying relative orbit determination using the double-differenced carrier phase of China's Bei-Dou navigation system as the main observable. The reduced dynamic technique combines the benefits of kinematic positioning techniques with those of a fully dynamic trajectory modeling to determinate the relative orbit using an extended Kalman filter, where the empirical accelerations are estimated using a first-order Gauss–Markov process noise model. In addition, the augmented filter state is estimated to compensate the incomplete dynamic model for better precision of the orbit solution. A simulated LEO scenario is established to investigate the performance of the proposed filtering schemes. The relative navigation results indicate that the filter provides accurate and compatible solution, which match an external reference solution to millimeter level when using the single-frequency measurements. [View Full Paper]

### AAS 14 – 382

**The Elliptic Rendezvous Problem in DROMO Formulation**

**Javier Roa** and **Jesús Peláez**, Space Dynamics Group, Technical University of Madrid (UPM), Madrid, Spain

The extension of DROMO formulation to relative motion is evaluated. The orbit of the follower spacecraft can be constructed through differences on the elements defining the orbit of the leader spacecraft. Assuming that the differences are small, the problem is linearized. Typical linearized solutions to relative motion determine the relative state of the follower spacecraft at a certain time step. Because of the form of DROMO formulation, the performance of a frozen-anomaly transformation is explored. In this case, the relative state is computed for a certain value of the anomaly, equal for leader and follower. Since the time for leader and follower do not coincide, the implicit time delay needs to be corrected to recover the physical sense of the solution. When determining the relative orbit, numerical testing shows significant error reductions compared to previous linearized solutions. [View Full Paper]

**AAS 14 – 383**

**Optimal Control of Two-Craft Electromagnetic Formation in Circular Orbit**

**Xu Zengwen**, **Shi Peng** and **Zhao Yushan**, School of Astronautics, Beihang University, HaiDian District, Beijing, China

Optimal reconfigurations of two-craft electromagnetic formation in low earth circular orbit are discussed. Equations of motion for two-spacecraft electromagnetic formation are derived according to the motion of tethered satellite. Three optimality criteria considered are minimum time, minimum acceleration, and minimum control acceleration. Two examples are presented to demonstrate the feasibility with different DOFs. The two-point-boundary-value problem is numerically solved via Gauss pseudo-spectral methods. A general framework of calculating control currents in electromagnetic coils according to the required control forces is presented. Analytical solutions of control currents for the case of two-craft are derived considering energy consumption equilibrium. [View Full Paper]

**AAS 14 – 384**
**(Paper Withdrawn)**

## SESSION 18: SPACECRAFT GUIDANCE AND CONTROL
**Chair: Angela Bowes, NASA Langley Research Center**

**AAS 14 – 385**

**Internal Moving Mass Actuator Based Angle of Attack and Angle of Sideslip Control for Mars Entry Missions**

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

An internal moving mass actuator (IMMA) control system is proposed for controlling angle of attack and angle of sideslip for Mars entry downrange and cross-track guidance. Motivation for IMMAs arises from their ability to provide vehicle control moments without direct interaction with the external flowfield. This enables trajectory control without ablation concerns associated with flap control systems and design complexity and destabilization concerns associated with thruster based control systems. A general form of the attitude equation for the vehicle instantaneous center of mass frame is derived for n IMMAs that can translate and rotate within the vehicle. A Linear Quadratic Servo controller for a two IMMA configuration is synthesized to track reference angle of attack and sideslip commands. Simulation of the controller on the 8 Degree of Freedom nonlinear system for Mars entry guidance is provided demonstrating the ability to meet angles of attack and sideslip for downrange and cross-track guidance to a predetermined target. [View Full Paper]

### AAS 14 – 386

**Optimal Low-Thrust Transfer and Guidance Scheme for Geostationary Orbit Insertion**

**Hao Huang**, School of Astronautics, Beihang University, HaiDian District, Beijing, China; **Jian Li**, Shanghai Institute of Satellite Engineering, Shanghai, China; **Hongli Zhang**, **Yinrui Rao** and **Chao Han**, School of Astronautics, Beihang University, HaiDian District, Beijing, China

Unscented Kalman filter (UKF) parameter estimation technique is proposed for solving two-point-boundary-value-problem. A guidance scheme is developed by tracking certain orbital characteristics profiles which are constructed time independent from open-loop time-optimal transfer trajectories. Feed-back guidance is implemented by solving a time-fixed optimal control problem at each revolution. The techniques proposed for orbit transfer and guidance scheme design are applied to three GEO insertion missions. The performance is demonstrated through simulations. Furthermore, the orbit perturbation and the eclipse effects are considered in the study of guidance scheme.
[View Full Paper]

### AAS 14 – 387

**Near-Optimal Guidance for Precision Lunar Landing With a Combined Solid Rocket Motor and Liquid Propulsion System**

**Martin T. Ozimek** and **Timothy G. McGee**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

Previous lunar missions, such as NASA's Surveyor program, have effectively utilized a solid rocket motor to accomplish a large portion of the $\Delta V$ required for terminal descent, followed by dispersion-cleanup and soft-landing with a smaller liquid propulsion system. However, additional complexity is encountered when precision landing guidance is desired because steering is possible with both propulsion systems. This study presents a novel solution to this problem that addresses the need for rapid onboard computation and near-minimal liquid fuel usage. The minimum fuel guidance problem is approximated in both phases to obtain a near-optimal algorithm that is suitable for flight implementation. [View Full Paper]

**AAS 14 – 388**

**Near-Optimal Feedback Guidance for Aeroassisted Orbital Transfer Via Spatial Statistical Prediction**

**Pradipto Ghosh** and **Bruce A. Conway**, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.

Feedback control of constrained non-linear dynamical systems satisfying a certain optimality criterion and meeting a specified transfer objective in the state space is well recognized as one of the most challenging problems in control theory. One approach to computing optimal feedback policies is the well-known dynamic programming route of numerically solving the notoriously difficult Hamilton-Jacobi-Bellman partial differential equation directly. In this paper, the effectiveness of a new implementation of an alternate, and more tractable dynamic programming approach, the optimal feedback synthesis method, is demonstrated through an explicit guidance scheme for the heating-rate-constrained maneuver of an Aeroassisted Transfer Vehicle (AOTV). In optimal feedback synthesis, a feedback chart is constructed from a family of open-loop extremals, thus ensuring optimality with respect to any initial condition in the family. In this work, a solution to the AOTV optimal feedback synthesis problem is proposed using the Gaussian process spatial prediction method of universal kriging. A closed-form expression for the guidance law is derived, the performance of which is found to be very promising; initial atmospheric-entry errors due to simulated thruster misfiring are seen to be accurately corrected while closely respecting the algebraic state-inequality constraint. [View Full Paper]

**AAS 14 – 389**
**(Paper Withdrawn)**

**AAS 14 – 390**

**Maneuver Performance Assessment of the Cassini Spacecraft Through Execution-Error Modeling and Analysis**

**Sean Wagner**, Flight Path Control Group and the Cassini Navigation Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Cassini spacecraft has executed nearly 300 maneuvers since 1997, providing ample data for execution-error modeling and analysis. With maneuvers through 2017, opportunities remain to update the execution-error models and remove biases identified in maneuver executions. This manuscript focuses on how execution-error models can be used to judge maneuver performance, while providing a means for detecting performance degradation. Additionally, this paper describes Cassini's execution-error model updates in August 2012. An assessment of Cassini's maneuver performance through January 2014 is also presented. [View Full Paper]

## AAS 14 – 391

### Optimal Spin Rate Control of a Spinning Solar Sail for the Maximum-Radius Orbit Transfer Problem

**Go Ono** and **Yuya Mimasu**, Department of Aeronautics and Astronautics, University of Tokyo, Chuo, Sagamihara, Kanagawa, Japan; **Jun'ichiro Kawaguchi**, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Chuo, Sagamihara, Kanagawa, Japan

The attitude and orbit of a spinning solar sail can be controlled by the spin rate of the spacecraft. In this paper, an optimal spin rate control law of a spinning solar sail for the maximum-radius orbit transfer problem is derived. An optimal control problem is solved analytically and numerically, and the comparison of the analytical and numerical solutions proves their validity. The control method proposed in this paper extends the possibilities of spinning solar sails. [View Full Paper]

## AAS 14 – 392

**(Paper Withdrawn)**

## AAS 14 – 393

### A Gas Bearing Platform Attitude Control for Assessment of AOCS Systems

**V. Carrara**, **A. M. Oliveira** and **H. K. Kuga**, Space Mechanics and Control Division, National Institute for Space Research (INPE), São José dos Campos, S.P., Brazil

This paper presents a solution for the development, validation and testing of attitude control system for satellites with hardware-in-the-loop dynamics and control. The system is based on a gas-bearing platform in which several sensors and actuators, similar to those usually employed in satellites (engineering models) were fixed. Magnetometers and gyroscopes are easily incorporated to the platform, but sun sensors and star sensors are more difficult. The solar sensors are replaced by a tri-axes accelerometer, while the star sensor relies on direct night sky measurements. Although hot gas thrusters cannot be used, both magnetic torque coils and reaction wheels are feasible to be incorporated to the arrangement. The gas-bearing balancing process is critical for real satellite dynamic simulation and therefore the solution is addressed in this work, by means of a non-linear filtering of the sensor readings. The filtering process also obtains the platform mass properties. In order to increase the filter accuracy the gyroscopes were calibrated; the calibration results are also presented here. Finally, an attitude controller was implemented in the platform and the control performance was analyzed and shown together with the conclusions. [View Full Paper]

## AAS 14 – 394

**(Paper Withdrawn)**

## AAS 14 – 395

### Design of the Attitude Control Subsystem of IITMSAT, a Geomagnetic-Field-Pointing Satellite

**Deepti Kannapan**, Department of Mechanical Engineering, University of California, Santa Barbara, California, U.S.A.; **Gourav Saha**, Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai, India; **Sruteesh Kumar**, Department of Engineering Design, Indian Institute of Technology Madras, Chennai, India; **Akshay Gulati**, Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai, India

The IITMSAT project is a student satellite initiative of the Indian Institute of Technology Madras. It is a nanosatellite with a scientific mission involving measuring proton and electron fluxes in the Earth's magnetosphere to characterize their interactions with electromagnetic waves. The scientific mission places requirements on the attitude control subsystem that the attitude be autonomously maintained such that one axis of the satellite tracks the geomagnetic field direction. This must be achieved using minimal hardware due to power and mass restrictions. A system to track the time-varying geomagnetic field vector is designed by a combination of analytical and numerical techniques. A novel approach of switching between two control laws, each controlling a subset of the states, is taken to achieve a high level of performance with purely magnetic actuation. [View Full Paper]

## SESSION 19: SPACECRAFT DYNAMICS
**Chair: Jay McMahon, University of Colorado**

### AAS 14 – 396
### Comparison of Gravitational, Third-Body, and Radiation Pressure Perturbations in Orbit Propagation

**Keric A. Hill** and **Charles J. Wetterer**, Integrity Applications Inc. (Pacific Defense Solutions), Kihei, Hawaii, U.S.A.; Moriba K. Jah, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

Recent research has highlighted the need for physically consistent radiation pressure and Bidirectional Reflectance Distribution Function (BRDF) models for precise orbit propagation. This paper seeks to evaluate the impact of BRDF-consistent radiation pressure models compared to a selection of other orbit perturbations in the equations of motion for orbit propagation. The differences in orbital position arising because of the addition of a particular force model are plotted as a function of time for various space objects in different orbits. This is done in two different ways. In the first, the initial position and velocity of the space object is kept fixed, and the orbital position difference between a baseline orbit and the perturbed orbit are plotted as a function of time. In the second, the results are plotted after differentially correcting the initial conditions of the trajectory with the altered force model so it has the least root mean square difference from the baseline. This effectively eliminates the secular component of the trajectory differences and leaves only the periodic component, which is more representative of the orbit error which would be seen when performing orbit determination with an imperfect force model. The trajectories are perturbed with a variety of effects including variations in Earth's gravity field, tides, third-body gravity, radiation pressure, drag, and the SGP4 analytic propagator. [View Full Paper]

## AAS 14 – 397

### Comparison of Solar and Thermal Radiation Accelerations of Deep-Space Satellites

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

Precise navigation of interplanetary satellites demands high-fidelity modeling of the forces that may affect the orbit. Whereas the relevant gravitational forces are known to very good precision, appreciable accelerations are also generated by non-conservative small forces like solar radiation pressure. Another small force is caused by the recoil of re-emitted thermal radiation from spacecraft surfaces. The paper summarizes the solar and thermal radiation models that enhance the cruise-phase orbit prediction and determination precision of ESA interplanetary spacecraft (i.e., Rosetta, Mars Express, and Venus Express). Also predictions are given for the Bepi Colombo composite spacecraft during its cruise phase. The models provide the expected accelerations as functions of the heliocentric distance and the satellite's thermo-optical parameters. In contrast to the effects induced by the solar radiation, the accelerations due to the thermal radiation are dominated by the body surfaces rather than the solar arrays for the four satellites considered here. Furthermore, thermal radiation effects generate much more appreciable acceleration components in the normal-to-Sun direction. [View Full Paper]

## AAS 14 – 398

### Saturated Attitude Control With Almost Global Finite-Time Stabilization

**Haichao Gui**, **Tingxuan Huang**, **Shijie Xu** and **Lei Jin**, School of Astronautics, Beihang University, HaiDian District, Beijing, China

The problem of finite-time attitude stabilization of a rigid spacecraft is revisited. First, homogeneous system theory is utilized to design a simple proportional-derivative (PD) type saturated finite-time controller (SFTC) based on quaternion, which avoids the undesirable unwinding phenomenon. Strict proof shows that the quaternion-based SFTC ensures almost global finite-time stability of the resulting closed-loop systems. Moreover, the proposed SFTC not only yields bounded control torques, but also possesses robustness to large inertia uncertainties of the spacecraft since they are completely independent of the spacecraft inertia. Numerical results demonstrate the effectiveness and superiority of the proposed controllers. [View Full Paper]

## AAS 14 – 399

### An Energy-Matching Optimal Control Method for Consensus of Spacecraft Cluster Flight

**Zhou Liang**, **Luo Jianjun**, **Zhang Bo**, **Su Erlong** and **Gong Baichun**, School of Astronautics, Northwestern Polytechnical University, Xi'an, China

This paper presents an optimal control method for consensus of spacecraft cluster flight under a kind of energy matching condition. Firstly, the relationship between energy matching and spacecraft periodically bounded relative motion is analyzed, and the spacecraft energy matching principle is applied to configure the initial conditions. Then, the period-delayed errors are employed as state variables to establish the period-delayed errors dynamics model of a single spacecraft and the cluster. Next a novel spacecraft cluster feedback control law with coupling gain is designed, so that the spacecraft cluster periodically bounded relative motion consensus problem is transformed into a period-delayed errors state consensus problem. Based on the consensus region theory in the research of multi-agent system consensus issues, considering the spacecraft information cluster topology relationship as well, the coupling gain can be obtained to meet the consensus region. Linear quadratic regulator (LQR) based optimal control approach is used to determine the feedback control gain matrix. This method can realize the synchronization of spacecraft cluster period-delayed errors, leading to the semi-major axis (SMA) tending to be consistent and the energy-matching of spacecraft cluster. Then spacecraft can emerge the global coordination cluster behavior. Finally the feasibility and effectiveness of the present energy-matching optimal consensus for spacecraft cluster flight is verified through numerical simulations. [View Full Paper]

## AAS 14 – 400

### A Unique Maiden Device for Propulsion and a Unique Maiden Device for Lift

**Hsien-Lu Huang**, United Space Alliance, NASA, Houston, Texas, U.S.A.;
**Hui-Lien Peng Huang**, Webster, Texas, U.S.A.

Based on the published finding of the authors as shown in Reference 1 cited in the full paper, in this article two new unique maiden devices have been developed and described. One is for propulsion force, and the other is for providing lift force. Because the derivation is independent of the environment where the devices are in, these devices can be used in air, sea, land, space, and interstellar flights. For easier demonstration, c feet long copper cylinder or c feet thick copper disk of b feet radius circular cross-section is used for both devices. [View Full Paper]

**AAS 14 – 401**

**A General Dynamics Model and Geometric Variational Integrator for Spacecraft With Variable Speed Control Moment Gyroscopes**

**Sasi Prabhakaran Viswanathan** and **Amit Sanyal**, Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, New Mexico, U.S.A.; **Frederick Leve**, Air Force Research Laboratory, Kirtland Air Force Base, Albuquerque, New Mexico, U.S.A.

An attitude dynamics model of spacecraft with variable speed control moment gyroscope (VSCMG), is obtained using the framework of geometric mechanics. This attitude dynamics formulation relaxes some standard assumptions, that are made in the prior literature on control moment gyroscopes and provides a general dynamics model. The dynamics equations show the complex nonlinear coupling between the internal degrees of freedom associated with the VSCMG and the spacecraft base body attitude degrees of freedom. General ideas on how this coupling can be used to control the angular momentum of the base body of the spacecraft using changes in the momentum variables of a finite number of VSCMGs, are provided. A special case of three VSCMGs arranged in tetrahedron configuration is considered. A control scheme using three VSCMG for an attitude pointing maneuver in the absence of external torques and when the total angular momentum of the spacecraft is zero, is presented. Geometric Variational Integrators are constructed for this underactuated system and the control scheme is numerically validated. [View Full Paper]

**AAS 14 – 402**
**(Paper Withdrawn)**

**AAS 14 – 403**

**Incorporating Physical Considerations in the Design of Repetitive Controllers**

**Jianzhong Zhu** and **Richard W. Longman**, Department of Mechanical Engineering, Columbia University, New York, New York, U.S.A.

Repetitive control (RC) can be used in spacecraft to control active vibration isolation mounts for fine pointing equipment, isolating the equipment from vibrations sources such as slight imbalance in a momentum wheel, in reaction wheels, or control moment gyros. RC can in theory completely eliminate the influence of a periodic disturbance of known period. Effective RC design methods have been developed by the authors and co-workers, that create FIR compensators mimicking the inverse system frequency response. This paper studies the optimization of the design parameters. Because such designs eliminate all periodic error harmonics up to Nyquist frequency, the FIR compensator gains can be large. This is studied, in particular as related to measurement noise. Actuator limitations, robustness to model error, and noise can suggest that one should cut off the learning process at sufficiently high frequency. Methods of producing a cutoff, and of influencing the size of the gains are considered, including: adjustment of the sample rate, penalizing large gains in the FIR design, using a high frequency cutoff in the cost function for the FIR design, using a zero-phase low-pass filter of the repetitive control action, and combinations of these. These results aim to guide the user in tuning the design parameters available when creating repetitive control systems.
[View Full Paper]

**AAS 14 – 404**
**(Paper Withdrawn)**

**AAS 14 – 405**
**(Paper Withdrawn)**

**AAS 14 – 406**

**Elevating Ordinary Differential Equations to the Complex Domain – A Simple Cookbook Example**

**Donald Hitzl** and **Frank Zele**, Lockheed-Martin Advanced Technology Center (retired); **Alan Zorn**, Department of Aeronautics and Astronautics, Stanford University, Stanford, California, U.S.A.

A very simple first-order ordinary differential equation is elevated to the complex domain. The analytic solution is immediately available. However, the analytic solution can also be obtained by integrating the complexified differential equations in four variables. The first-order coherences given by the Cauchy-Riemann equations are displayed together with the newly-discovered second-order analytical coherences given by the perturbation derivative. As a result, new physical meanings are obtained for complex analytic functions. Through complexification, new physical meanings can be applied to space flight mechanics revealing additional intuition and insight. [View Full Paper]

## SESSION 20: EARTH MISSIONS
### Chair: Aline Zimmer, Jet Propulsion Laboratory

**AAS 14 – 407**

**Optimization of Lattice Flower Constellations for Intensity Correlation Interferometric Missions**

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

This paper addresses the problem of designing optimal satellite constellations for *Intensity Correlation Interferometry* (ICI) missions based on the intensity correlation approach. Optimality in ICI missions requires maximizing the coverage of the frequency resolution disc. The 3-D Lattice Flower Constellations theory, which includes the $J_2$ gravitational perturbation, is here applied to optimize the constellation design. Optimization is performed using a Genetic Algorithm with two types of fitness functions to estimate the optimal design parameters. The fitness function describing the design optimality is constrained by altitude range to avoid too low perigee (drag) and too high apogee (inner Van Allen belt). Numerical results clearly show the resolution disc coverage as a function of the number of satellites and the frequency discretization bin number (pixels). Performances and results are provided to help select a fitness function for the mission and constellation designer. [View Full Paper]

**AAS 14 – 408**

**A Numerical Simulation-Based Design of Operational Orbits for Multiple Sun-Synchronous Spacecraft**

**Tae Soo No** and **Hwayeong Kim**, Department of Aerospace Engineering, Chonbuk National University, Jeonju, Republic of Korea; **Ok-Chul Jung** and **Dae-Won Chung**, Korea Aerospace Research Institute, Daejeon, Republic of Korea; **Jinheng Choi**, Department of Aerospace Engineering, Chonbuk National University, Jeonju, Republic of Korea

In this paper, a purely numerical simulation and optimization approach is proposed in designing a sun-synchronous orbit with additional operation requirements such as maximizing access time to a target on the ground. A high fidelity model of the Earth's gravitational attraction as well as all other perturbations are fully accounted for, and the orbit design problem is reformulated as a nonlinear optimization problem using sun-synchronicity, ground track repeatability, target access time, and ground station contact time during a certain period as cost function and/or constraint conditions. Examples show that both the sun-synchronicity and the ground-track repeatability are greatly improved compared to J2-based sun-synchronous orbits, while the orbit of multiple spacecraft can be designed in such a way that helps best utilize limited space and ground resources. [View Full Paper]

## AAS 14 – 409

### Architecture Analysis Framework for Space Systems Supported by On-Orbit Refueling

**SeungBum Hong** and **Jaemyung Ahn**, Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology (KAIST), Yuseoung-gu, Daejeon, Republic of Korea

This paper proposes a general framework to compare the cost and benefit of different space system architecture alternatives, including architectures with support of on-orbit refueling function. The framework consists of four steps. In the first step, identifying an event tree helps reveal provides to reveal uncertainties associated the events that could happen during the operation and elements for constructing framework. In the second step, identifying architecture candidates that can achieve goals of missions. Cost and benefit models are developed with considering characteristics of each candidate. In the third step, the Monte Carlo simulation is performed to compare architecture candidates and finds out the maximum value of on-orbit refueling service. In the last step, post-analysis is performed to get more insights on the architecture candidates. Through performing these steps, decision makers will have an opportunity to determine whether on-orbit refueling option is worth considering in the early stage of design. A case study is also carried out to demonstrate the framework. [View Full Paper]

## AAS 14 – 410

### Resonant Perturbations With the Earth's Gravity Field

**Jérôme Daquin**, CNES/THALES/IMCCE, Thales Services, Département Espace, Toulouse, France; **Florent Deleflie**, IMCCE/Observatoire de Paris, Paris, France; **Pierre Mercier**, Thales Services, Département Espace, Toulouse, France; **Jérôme Pérez**, ENSTA Paristech, Laboratoire de Mathématiques Appliquées, Palaiseau, France

We confront stability results coming from the *mean motion theory* and the *osculating theory* in orbital mechanics. The dynamical area studied correspond to the (2 : 1) tesseral resonance. We present Fast Lyapunov Indicator stability maps, based on the integration of the variational equations, realized in various dynamical configurations and in particular for eccentric orbits. Our main conclusions supports the idea that the tesseral chaos is not sensitive to the averaging process and validate, on a stability point of view, the minimal model implemented in our mean orbit propagator.
[View Full Paper]

**AAS 14 – 411**

**Revisiting the DSST Standalone Orbit Propagator**

**Paul J. Cefola**, Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Amherst, New York, U.S.A.; **Zachary Folcik**, MIT Lincoln Laboratory, Lexington, Massachusetts, U.S.A.; **Romain Di-Costanzo** and **Nicolas Bernard**, CS Communications & Systemes, Toulouse, France; **Srinivas Setty**, Space Situational Awareness, Deutsches Zentrum fur Lüft- and Raumfahrt (DLR), German Space Operations Center (GSOC), Wessling, Germany; **Juan Félix San Juan**, Department of Mathematics and Computation, Universidad de La Rioja, Logroño, Spain

The goal of the Draper Semi-analytical Satellite Theory (DSST) Standalone Orbit Propagator is to provide the same algorithms as in the GTDS orbit determination system implementation of the DSST, without GTDS's overhead. However, this goal has not been achieved. The 1984 DSST Standalone included complete models for the mean element motion but truncated models for the short-periodic motion. The 1997 update included the short-periodic terms due to tesseral linear combinations and lunar-solar point masses, 50 x 50 geopotential, and J2000 coordinates. However, the 1997 version did not demonstrate the expected improved accuracy. Three projects undertaken by the authors since 2010 have led to the discovery of additional bugs in the DSST Standalone which are now resolved. [View Full Paper]

**AAS 14 – 412**
**(Paper Withdrawn)**

**AAS 14 – 413**

**The Observation of Micron-Size Debris Environment by Using Multi-Satellite Network for the IDEA Project**

**Mitsuhiko Tasaki**, **Toshiya Hanada**, **Kazuaki Ae**, **Koki Fujita** and **The IDEA Project Team**, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka, Japan

Space System Dynamics Laboratory in Kyushu University has initiated IDEA, the project for in-situ Debris Environmental Awareness to correctly understand current space debris problem. In order to estimate debris environment on orbit, we use a constellation of small satellites which are covered with a detector of dust impact. In this paper, some results of a mission analysis which demonstrates collision flux for the dust detectors are shown, as well as an outline of our project are. Future work to determine an orbit of the debris cloud which are generated from certain breakup events are also described. [View Full Paper]

## AAS 14 – 414

### Safe Release of a Picosatellite From a Small Satellite Carrier in Low Earth Orbit

**Martin Wermuth** and **Gabriella Gaias**, German Space Operations Center (GSOC/DLR), Oberpfaffenhofen, Wessling, Germany; **Simone D'Amico**, Department of Aeronautics & Astronautics, Stanford University, Stanford, California, U.S.A.

The BIROS satellite, which is scheduled for launch in 2015 into a low Earth orbit, will carry onboard a picosatellite and subsequently release it through a spring mechanism with a fixed velocity. In the frame of the AVANTI experiment, the BIROS satellite will perform proximity maneuvers in a mid-range formation with the picosatellite, based solely on optical navigation through its onboard camera. Therefore it is necessary to keep the relative distance of the two spacecraft within certain limits. This is contradicted by the fact, that the spring mechanism is designed to create a large and safe separation between the two spacecraft.

In this paper a maneuver strategy is developed in the framework of relative orbital elements. The goal is to avoid any risk of collision on one side and to mitigate the possibility of formation evaporation on the other side. Main design drivers are several uncertainties—most prominently the performance uncertainty of the release mechanism. The analyzed strategy consists of two maneuvers: the separation itself and a drift reduction maneuver of the BIROS satellite after 1.5 revolutions. Afterwards a third maneuver is to be performed to minimize the residual drift, estimated through an orbit determination with radar tracking.

The selected maneuver parameters are validated in a Monte Carlo simulation. It is demonstrated that the risk of formation evaporation is below 0.1% as well as the eventuality of a residual drift towards the carrier. In the latter case formation safety is guaranteed by a passive safety achieved through a proper relative eccentricity/inclination vector separation. [View Full Paper]

## AAS 14 – 415

### Designing Chip-Sized Spacecraft for Missions to L4/L5 Lagrangian Points in the Earth-Moon System

**Lorraine M. Weis** and **Mason Peck**, Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York, U.S.A.

Chip-scale spacecraft represent a novel, inexpensive way to explore the triangular Lagrangian points of the Earth-Moon system. The dynamics of particles in these regions have intrigued scientists for decades. This paper examines the feasibility of a mission using a swarm of chip-scale spacecraft rather than a monolithic spacecraft strategy. In aggregate, the swarm will maintain a position near the triangular points, thus establishing distributed sensors through the region. We present simple navigational strategies for this proposed swarm, suited for the lower power and mass requirements of chip-scale spacecraft. Such a chip-spacecraft mission would be a valuable precursor to further space development in these regions. [View Full Paper]

**AAS 14 – 416**
**(Paper Withdrawn)**

**AAS 14 – 417**
**(Paper Withdrawn)**

## SESSION 21: OPTICAL NAVIGATION
**Chair: Lincoln Wood, Jet Propulsion Laboratory**

**AAS 14 – 418**

### Asteroid Characterization Via Stellar Occultation: SNR Calculation and Observation Opportunities

**David C. Hyland**, Department of Aerospace Engineering, Dwight Look College of Engineering, Texas A&M University, College Station, Texas, U.S.A.;
**Haithem A. Altwaijry**, Space Research Institute, King Abdulaziz City for Science and Technology, Riyadh, Kingdom of Saudi Arabia

This paper develops additional results supporting the novel asteroid characterization technique which uses the theory of the diffraction of shadows and phase retrieval technology to determine the size and shape of hazardous Near-Earth Asteroids (NEAs) via stellar occultation. In particular, we obtain an estimate of the SNR with which the silhouette of NEAs in the 140-to-40 meter diameter class can be determined. Via a Monte Carlo approach we estimate the rate at which a given NEA is occulted by a star of given apparent magnitude. Thanks to the abundance of stars above 10th magnitude, occultation observations will be reasonably frequent. [View Full Paper]

### AAS 14 – 419

**Fuzzy Logic Approach Strategy Based Feature Point Measurements for Asteroid Exploration Guidance**

**Hongliang Ma**, **Shijie Xu** and **Kai Wang**, Department of Aerospace Engineering, School of Astronautics, Beihang University, HaiDian District, Beijing, China

Considering strong coupling of mathematic model of simultaneously controlling the relative position and direction of probe to asteroid surface, difficult determination of the irregular gravity model of asteroid, and uncertainty changes of asteroid motion parameters, a fuzzy logic approach strategy based feature point measurements of asteroid surface is presented for asteroid exploration landing mission. In the new approaching guidance technology, based on measured and sufficient feature points, the relative position and landing direction as fuzzy variables are firstly and simultaneously controlled in the same reference frame, and then, with the probe controlled by flywheels to track of the normal vector of landing plane measured by laser imaging detection and ranging (LIDAR) system, the relative position and their first-order derivates as only fuzzy variables are controlled by using a single feature point in the probe body frame when probe is sufficiently close to asteroid surface. The presented fuzzy control method does not need establishing the complete mathematic model of controlled relative motion object. Numerical simulations are undertaken to verify the feasibility of the designed fuzzy logic approach strategy, and evaluate its robustness and adaptability for the fuzzy variables with the navigation errors caused by the uncertainty changes of the asteroid spinning angular velocity and the inaccurate gravity model of asteroid. [View Full Paper]

### AAS 14 – 420

**Lidar and Optical-Based Autonomous Navigation for Small Body Proximity Operations**

**Matthew J. Abrahamson**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.;
**Shyam Bhaskaran**, Outer Planet Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Future missions to small bodies will require greater onboard navigation capabilities to execute orbit surveys, landings, impacts, and sample return scenarios. This paper explores the performance of an onboard navigation system using lidar measurements of slant range to the small body surface and optical measurements of surface landmarks during orbiting and landing scenarios. Performance relative to shape model fidelity is explored, with a simple triaxial ellipsoid shape model compared to a highly refined faceted plate model. A three-beam lidar measurement strategy is explored, with results indicating achievable landing accuracies on the order of 2–3 meters if combined with landmark tracking. [View Full Paper]

**AAS 14 – 421**

**Optical and Infrared Sensor Fusion for Hypervelocity Asteroid Intercept Guidance**

**Joshua Lyzhoft**, **Dalton Groath** and **Bong Wie**, Asteroid Deflection Research Center, Department of Aerospace Engineering, Iowa State University, Ames, Iowa, U.S.A.

In this paper we investigate the technical feasibility of a new terminal guidance system architecture for a hypervelocity asteroid intercept vehicle (HAIV). All previous terminal guidance system studies for an asteroid intercept problem have mainly considered optical cameras due to their cost-effective nature and acceptable target tracking performance as was demonstrated by Deep Impact mission. However, this paper examines a concept of blending optical and infrared (IR) sensors for reliable target tracking and robust intercept of small (50–150 m) asteroids. A preliminary design study for developing a reference 50-kg class IR sensor system for a 1000-kg class HAIV is described, and the intercept performance of a closed-loop terminal guidance system employing both optical and IR sensors is demonstrated. [View Full Paper]

**AAS 14 – 422**

**Small Body Optical Navigation Using the Additive Divided Difference Sigma Point Filter**

**Corwin Olson** and **Ryan P. Russell**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas, U.S.A.;
**James R. Carpenter**, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Sequential methods of state estimation are evaluated for small body autonomous navigation using only optical landmark measurements. Sequential techniques are employed due to the inherently sequential nature of onboard real-time navigation and the limited computational resources of onboard processors. All spacecraft state parameters (position, velocity, and attitude) are directly estimated from the optical landmark measurements to minimize measurement information loss. The standard Extended Kalman Filter (EKF) and the Additive Divided-difference sigma point Filter (ADF) are employed in various mission scenarios, with Monte Carlo analyses to compare the different techniques. The two-level nested Batch Least Squares (BLS) method used in previous studies is transformed into a sequential technique by implementing a "sliding window", and this method is compared to the EKF and ADF. The ADF performs favorably versus the EKF and nested sliding BLS after an initial convergence period, especially for scenarios with sparse measurements and for attitude estimation. Planners and operators for current and future missions that may use landmark optical navigation about small bodies could benefit from the sequential single-filter architecture and the tuning parameters used in this study. [View Full Paper]

**AAS 14 – 423**
**(Paper Withdrawn)**

## SESSION 22: SPACE ENVIRONMENT
**Chair: Marcus Holzinger, Georgia Institute of Technology**

### AAS 14 – 424

### Orbital Evolution of Dust Particles Originating From Jupiter's Trojan Asteroids

**Aline K. Zimmer** and **Keith Grogan**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Planetary Science Decadal Survey calls for an exploration mission for the in-situ observation and characterization of Trojan asteroids residing in the vicinity of Jupiter's L4 and L5 libration points. Since the dust environment encountered on a mission to Jupiter's Trojan asteroids could potentially put the mission or spacecraft at risk and observations of dust particles at such large distances from Earth's orbit are infeasible with terrestrial or current in-space telescopes, the objective of this study is to use an astrodynamical modeling approach to characterizing the dust environment in the vicinity of Jupiter's Trojans. Dust particles are assumed to separate from Trojan asteroids and the orbital evolution of these particles under the influence of planetary gravitational perturbations, radiation pressure, Poynting-Robertson drag, and solar wind drag is studied. The initial distribution of dust particles is derived from the currently known population of Trojan asteroids and then propagated for 500,000 years. It is observed that larger particles remain captured in Jupiter's 1:1 MMR and in the vicinity of the L4 and L5 libration points for the duration of the integration. Smaller particles leave the 1:1 MMR earlier and become trapped in higher order MMRs over time where they remain captured for durations on the order of 500 to 1,500 years before they move on. Particles smaller than 16 $\mu$m are expelled from the vicinity of Jupiter's orbit in timespans on the order of few tens of thousands of years after a fragmentation occurs. Combining these results with the frequency with which such fragmentation events occur and the number of particles released by the event as a function of particle size in subsequent research, the dust environment in the vicinity of Jupiter's Trojan asteroids can be fully described and its potential risk to a spacecraft and mission can be assessed. [View Full Paper]

## AAS 14 – 425

### Space Weather Influence on Relative Motion Control Using the Touchless Electrostatic Tractor

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

With recent interest in the use of electrostatic forces for contactless tugging and attitude control of noncooperative objects for orbital servicing and active debris mitigation, the need for a method of remote charge control arises. In this paper, the use of a directed electron beam for remote charge control is considered n conjunction with the relative motion control. A tug vehicle emits an electron beam onto a deputy object, charging it negatively. At the same time, the tug is charged positively due to beam emission, resulting in an attractive electrostatic force. The relative position feedback control between the tug and the passive debris object is studied subject to the charging being created through an electron beam. Employing the nominal variations of the GEO space weather conditions across longitude slots, two electrostatic tugging strategies are considered. First, the electron beam current is adjusted throughout the orbit in order to maximize this resulting electrostatic force. This open-loop control strategy compensates for changes in the nominally expected local space weather environment in the GEO region to adjust for fluctuations in the local plasma return currents. Second, the performance impact of using a fixed electron beam current on the electrostatic tractor is studied if the same natural space weather variations are assumed. The fixed electron beam current shows a minor performance penalty (< 5%) while providing a much simpler implementation that does not require any knowledge of local space weather conditions.
[View Full Paper]

## AAS 14 – 426

### Determining Orbits That Can be Controlled by Natural Forces

**Thais C. Oliveira** and **Antonio F. B. A. Prado**, National Institute for Space Research (INPE), Space Engineering Technology, Space Mechanics and Control, São José dos Campos, S.P., Brazil; **Arun K. Misra**, McGill University, Department of Mechanical Engineering, Montreal, Quebec, Canada

This paper aims to map orbits based on the integral of the magnitude of the perturbation forces. Particularly, the effects of the inclination and the eccentricity of the orbit in those mappings are studied. The perturbation forces considered here are the solar radiation pressure, the LuniSolar perturbation, the zonal harmonics $J_2$ to $J_4$ and the atmospheric drag. The results of these integrals are the velocity increment that the perturbation delivers to the satellite. The possibility of using a solar sail to reduce the effects of the other perturbations acting on the satellite is considered using this approach.
[View Full Paper]

### AAS 14 – 427

**Impact Probability Analysis for Near-Earth Objects in Earth Resonant Orbits**

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

Accurate estimation of the impact probability of near-Earth objects (NEOs) is required for planning a space mission to mitigate their threat. There are several methods that can be used to determine the odds of an asteroid impacting the planet. Methods incorporating analytic encounter geometry analyses, target B-planes, and analytic keyhole and resonant orbit theory are useful in the sense that they can aid in obtaining a quick rough estimation of the impact probability. Other methods using high-precision orbital dynamic simulations, taking into account non-conservative perturbations, allow for a better, more accurate estimate of the impact probability. Taking the advantages of a direct numerical simulation approach, incorporating analytic keyhole theory, this paper presents a new computational approach to accurately estimating the impact probability of NEOs, especially those in Earth resonant orbits. [View Full Paper]

### AAS 14 – 428

**Passive Electrostatic Charging of Near-Geosynchronous Space Debris HAMR Objects and its Effects on the Coupled Object Dynamics**

**C. Früh**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A. / Department of Mechanical Engineering University of New Mexico, Albuquerque, New Mexico, U.S.A.;
**D. Ferguson**, **C. Lin** and **M. K. Jah**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

Anomalies caused by charging of operational satellites is a well investigated topic. But little to no attention has been paid to the charging of non-operational objects. The orbital and attitude dynamics however, are significantly altered by passive electrostatic charging of objects and their motion relative to the Earth magnetic field. This paper investigates the effect of charging in the near geostationary regime of a special class of space debris objects. So-called high area-to-mass ratio (HAMR) objects are very sensitive to perturbations. This paper shows the significant effect charging has on their orbit and attitude evolution. [View Full Paper]

### AAS 14 – 429

**(Paper Withdrawn)**

## SESSION 23: ORBIT DETERMINATION II
**Chair: Geoffrey Wawrzyniak, a.i. Solutions**

### AAS 14 – 430

**Precise Non-Gravitational Forces Modeling for GOCE**

**Francesco Gini**, **Massimo Bardella** and **Stefano Casotto**, Università degli Studi di Padova, Padova, Italy

GOCE was launched in 2009 at 250 km altitude to recover Earth's static gravity field. As part of the GOCE-Italy project, we carried out the precise modeling for the radiation pressure and the aerodynamic effects on this satellite. This analysis has been performed to drastically reduce the mismodeling of the non-gravitational forces, in order to be able to estimate the ocean tides parameters from the LEO satellites orbital perturbation. A new software ARPA (Aerodynamics and Radiation Pressure Analysis), which takes advantage of the raytracing technique, has been designed and developed to accurately model the non-gravitational perturbations. ARPA can compute the Solar Radiation Pressure (SRP), Earth Radiation Pressure (ERP), the spacecraft Thermal Re-Radiation (TRR) and the aerodynamic forces and torques acting on any satellite with a high level of accuracy. The adopted methodologies and procedure are presented in this paper, and the results of the tests on GOCE are illustrated and discussed. The NAPEOS (NAvigation Package for Earth Observation Satellites) software, developed and maintained at ESA/ESOC, was upgraded to make use of the new ARPA inputs and adopted to perform the tests on GOCE. The tests were performed on 30 consecutive daily arcs, starting at the beginning of the GOCE science phase on 1st November 2009. The results for the radiation test cases show a significant reduction of the empirical accelerations, especially in the cross-track direction, of about the 20% for the SRP, 12% for the ERP albedo, 13% for the ERP infrared and 20% for the TRR with respect to the standard NAPEOS force modeling (cannon-ball). For the aerodynamics, an important reduction of the post-fit RMS from 7:6 to 7:3 *mm* has been observed with the new ARPA model, and the a reduction from 4:6 to 4:2 *cm* of the distance of the orbits computed with ARPA from the official reduced-dynamics GOCE orbits (Precise Science Orbit) has been computed. The obtained results confirm the goodness of the modeling and techniques of ARPA for all the non-gravitational perturbations computed for GOCE.

Even though the results are presented for the GOCE satellite, the new technique and software are adaptable to satellite of any shape, whether in Earth-bound orbit, or orbiting another planet, or cruising in interplanetary space. [View Full Paper]

## AAS 14 – 431

**Utilization of Uncertainty Information in 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.

In an initial orbit determination (IOD) problem with known sensor uncertainty characteristics, probabilistic information beyond the typical point solution may be derived. In previous work (AAS 13-822), the authors demonstrated methods of determining state uncertainty estimates directly from an angles-only IOD process. This paper extends the previous work by applying it to other IOD methods using angles-only observations, as well as simulating different orbits and observation geometries, including simultaneous measurements from multiple geographically distinct ground sites. We also explore performance for using the IOD state and uncertainty estimate as a starting point when processing additional observations. [View Full Paper]

## AAS 14 – 432

**LiAISON Tracking for a Lunar Far-Side Sample Return Mission**

**Ryan M. McGranaghan**, **Jason M. Leonard**, **Jeffrey S. Parker**, **George H. Born**, **Ann Dietrich** and **Siamak G. Hesar**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.

Autonomous orbit determination is conducted between a spacecraft orbiting at the Earth-Moon (EM-L2) point and a simulated lander ascending from the far-side lunar surface. Navigation of the vehicle from the lunar surface to an EM-L2 libration point orbit rendezvous is explored. Satellite-to-satellite tracking via Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) is used to estimate the lander's trajectory. Additionally, a set of tracking scenarios is explored, varying quantity and type of observation. A realistic ascent scenario is analyzed primarily based on key events and uncertainties specified by the Moon-Rise study. We study the navigation capabilities through both Crámer Rao lower bound covariance and Kalman filter state estimation analyses. The covariance analysis and full simulations show that the navigation solution for the lander's trajectory can be dramatically improved using LiAISON primarily in three ways: 1) reduction in the lowest attainable position uncertainty by 10-200 m throughout the entire lunar ascent trajectory, 2) improved short-arc absolute navigation solutions, and 3) improved mid-course maneuver estimation performance.
[View Full Paper]

## AAS 14 – 433

### Rapid Repeated Solving of the Kepler Equation Using the K-Vector Technique and Optimal Lookup Tables

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

This paper provides a method for (repeatedly) solving the Kepler equation using an optimal lookup table that provides the best possible accuracy for a limited table size. Motivation comes from various problems where the Kepler equation must be solved for a specific value of eccentricity, such as in Keplerian or $J_2$ performance analysis, conjunction analysis of satellite constellations, or any problem where repeated solving of the Kepler equation for the same elliptical orbit is needed. The proposed method requires pre-processing effort to build an optimal lookup table where linear interpolation provides an estimate solution of the Kepler Equation with an accuracy better than a specified tolerance. Access to the lookup table is performed using the *k*-vector technique, a search-less range searching technique. The proposed method is particularly well suited for GPU applications. The accuracy as well as the complexity analysis of the method is also provided. [View Full Paper]

## AAS 14 – 434

### Uncertainty Quantification for Angles-Only Initial Orbit Determination

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

This research addresses the issue of appropriately characterizing the range and range-rate solution space for the problem of angles-only initial orbit determination of resident space objects. In lieu of the techniques of Gauss or Lagrange, the use of the admissible region has been used to constrain hypotheses of range and range-rate pairs using the concept of the attributable vector as well as adding orbit energy and eccentricity constraints. This paper applies the transformation of variables technique to map measurement space uncertainty into the angle-rate and angle-acceleration as well as the range and range-rate domains using dynamics as the distribution link mechanism. This allows for improved characterization of state uncertainty distribution associated with the initial orbit determination process. [View Full Paper]

## AAS 14 – 435

**Reconstruction of Earth Flyby by the Juno Spacecraft**

**Paul F. Thompson**, **Matthew Abrahamson**, **Shadan Ardalan** and **John Bordi**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Juno spacecraft conducted a successful gravity-assist flyby of the Earth on 09 October 2013, putting the spacecraft on a trajectory to reach Jupiter in July 2016. The DSN tracking was supplemented by tracking from two ESA stations, giving us an unprecedented, near continuous level of tracking for an interplanetary spacecraft flyby of Earth. We discuss the process of reconstructing that trajectory, the challenges encountered in that effort, and the results. In particular, no anomalous velocity change was observed at or near perigee as has been observed in some of the previous Earth gravity assist flybys by other spacecraft. [View Full Paper]

## SESSION 24: AERONOMY SPECIAL SESSION
### Chair: David Finkleman, SkySentry Stratospace Technologies

**AAS 14 – 200**

**Impact: Integrated Modeling of Perturbations in Atmospheres for Conjunction Tracking**

**Alexei Klimenko**, **Sean Brennan**, **Humberto Godinez**, **David Higdon**, **Josef Koller**, **Earl Lawrence**, **Richard Linares**, **David M. Palmer**, **Michael Shoemaker**, **David Thompson**, **Andrew Walker** and **Brendt Wohlberg**, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.; **Moriba Jah** and **Eric Sutton**, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.; **Thomas Kelecy**, The Boeing Company, Colorado Springs, Colorado, U.S.A.; **Aaron Ridley**, University of Michigan, Ann Arbor, Michigan, U.S.A.; **Craig McLaughlin**, University of Kansas, Lawrence, Kansas, U.S.A.

The United States relies heavily on its space infrastructure for a vast number of applications, including communication, navigation, banking, national security, and research. However, NASA predicts that between now and 2030 orbital collisions will become increasingly frequent and could reach a runaway environment. This devastating scenario, also known as the Kessler Syndrome, has the potential to eventually destroy our assets in near-Earth space and result in a debris cloud that could make space itself inaccessible. Preventing the Kessler Syndrome requires, in addition to an object removal technique, a groundbreaking new orbital dynamics framework that combines a comprehensive physics-based model of atmospheric drag with an accurate uncertainty quantification of orbital predictions. The IMPACT project (Integrated Modeling of Perturbations in Atmospheres for Conjunction Tracking), funded by the Los Alamos National Laboratory Directed Research and Development office, has the goal to develop such an integrated system of atmospheric drag modeling, orbit propagation, and conjunction analysis with detailed uncertainty quantification to address the space debris and collision avoidance problem. We discuss the components and capabilities of the IMPACT framework and show a short demonstration of modeling interface and resulting 3D visualizations. [View Full Paper]

### AAS 14 – 330

**Multi-Model Orbital Simulation Development With Python**

**Sean M. Brennan**, **Michael A. Shoemaker**, **Andrew C. Walker**, **Humberto C. Godinez** and **Josef Koller**, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

The Integrated Modeling of Perturbation in Atmospheres for Conjunction Tracking (IMPACT) project integrates drag modeling, orbit propagation, and conjunction analysis to better predict collisions in orbit. This is built on, and propels the further development of, our integration architecture: *SysDevel*. The `sysdevel` Python package generically aids multi-model simulation development through model coupling, data visualization and collaborative software distribution. We describe in detail how *SysDevel* handles each of these tasks, and the ongoing challenges they present, as a case study of the IMPACT project's integration efforts. [View Full Paper]

### AAS 14 – 341

**Simultaneous Estimation of Atmospheric Density and Satellite Ballistic Coefficient Using a Genetic Algorithm**

**Michael A. Shoemaker**, **Andrew Walker** and **Josef Koller**, Space Science and Applications (ISR-1), Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

This research describes a new method to estimate simultaneously the spatially-resolved thermospheric neutral density and drag ballistic coefficient for a number of target satellites. A genetic algorithm is used to find an optimal set of density model parameters and ballistic coefficients that minimizes the position error, compared against assumed ground-based tracking of the satellites. The method has advantages over existing methods, which rely on *a priori* knowledge of the targets' ballistic coefficients in order to estimate the current state of the density. Numerical simulations show the feasibility of the method for a random set of 20 target satellites.[View Full Paper]

## AAS 14 – 436

### Gas-Surface Interactions for Satellites Orbiting in the Lower Exosphere

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

While decades of research have constrained the drag coefficients of low Earth orbit satellites below 500 km, little is known about drag coefficients above 500 km altitude. At altitudes below ~300 km, the adsorption of atomic oxygen to spacecraft surfaces has been well-established. Furthermore, the adsorption of atomic oxygen at altitudes ~500 km has been well fit with a Langmuir isotherm; however, there is disagreement between the Langmuir fit and fitted drag coefficients above 500 km altitude. Previous work with STELLA and the Calsphere satellites has indicated that gas-surface interactions are primarily diffuse, even at 700 km altitude. This finding is at odds with drag coefficient models based on adsorption models for atomic oxygen which lead to increasingly specular reflection at higher altitudes due to a sharp decline in atomic oxygen adsorption. There are several possible explanations for the disagreement of adsorption theory with previous work. These possibilities include erosion, atmospheric density biases, and deficiencies in the adsorption model. We explored the third option in a previous paper and found it unable to explain the disagreement. The first and second possibilities are explored in this work using an orbital propagator, IMPACT-prop, in conjunction with the empirical atmospheric model, NRLMSISE-00, to calculate fitted drag coefficients throughout the lifetime of a collection of spherical satellites. The satellites are analyzed for signatures of erosion (defined by a decrease in the drag coefficient over several months not due to changes in atmospheric properties) and atmospheric density biases. A few satellites, especially GFZ-1, are found to have an erosion signature; however, atmospheric density biases are far more widespread in the results and often lead to ambiguous conclusions regarding erosion. Atmospheric density biases and updated fitted drag coefficients for the STELLA and the Calsphere satellites help to resolve the disagreement between previous work and adsorption-based drag coefficient models. [View Full Paper]

**AAS 14 – 437**

**The Intersection of Satellite Aerodynamics and Aeronomy**

**David Finkleman**, SkySentry, LLC, Colorado Springs, Colorado, U.S.A.

The purpose of this review is to suggest how impediments to convergence of drag representations and atmospheric models can be addressed. Aeronomy strives for simple satellite shapes and gasdynamically inert surfaces that have relatively confident representations of aerodynamic forces in order to extract density. Astrodynamics deals with complex shapes whose drag is either unknown or very difficult to determine other than by having a confident description of the atmosphere. These are generally not interchangeable. Can astrodynamicists employ confidently drag inferred from simple shapes and even simple descriptions of orbits to determine and propagate trajectories of satellites with complex geometries in a highly perturbed force environment? The goals of AFOSR, Los Alamos, and ISO collaboration are to guide best use of drag inferences or atmospheres determined under conditions and assumptions different from that of practicing orbit analysts and aeronomists seeking to characterize the atmosphere synoptically. Different assumptions and characterizations are required for different tasks. One should not expect atmospheric characterizations inferred from extinction of elements of the solar spectrum to work well for orbit determination, although they should be exquisite for estimating electromagnetic transmission. Similarly, atmospheres inferred from satellite energy dissipation should not do well for electromagnetic transmission. We seek best practices while suffering these difficulties and eventually a confident and consensus description of satellite aerodynamics from first principles. [View Full Paper]

**AAS 14 – 438**
**(Paper Withdrawn)**

**AAS 14 – 439**
**(Paper Withdrawn)**

**AAS 14 – 440**
**(Paper Withdrawn)**

## AAS 14 – 441

**Comparison of Satellite Orbit Tomography With Simultaneous Atmospheric Density and Orbit Estimation Methods**

**Michael A. Shoemaker**, **Brendt Wohlberg**, **Richard Linares**, **David M. Palmer**, **Alexei Klimenko**, **David Thompson** and **Josef Koller**, Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

Satellite orbit tomography is a newly developed method for addressing the Dynamic Calibration of the Atmosphere (DCA). The focus of this paper is a side-by-side comparison with other DCA methods that use the raw tracking measurements and solve simultaneously for the orbit state and parameterized density correction. The main contribution of this work is to test the notion that, in general, an estimator benefits from using raw measurements to solve for the state, in contrast with an estimator that uses intermediate estimated quantities in place of the raw measurements. [View Full Paper]

## SESSION 26: DYNAMICS AND CONTROL OF LARGE SPACE STRUCTURES AND TETHERS

**Chair: Dr. Maruthi R. Akella, University of Texas at Austin**

## AAS 14 – 442

**(Paper Withdrawn)**

## AAS 14 – 443

**Tether Design Considerations for Large Thrust Debris De-Orbit Burns**

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

The use of tethers in space has been considered for many years. Most recently, there have been concepts that could involve tethers for towing objects in space. Active debris removal, asteroid retrieval, and satellite servicing may require a towing vehicle with thrusting capability to maneuver the object to be towed. Because a tether does not provide a rigid interface between the two objects, post-burn collision avoidance is a critical concern. Earlier work demonstrated exciting input-shaped towing strategies that resulted in the tug and debris aligning, post-burn, with the gravity gradient stable nadir axis thus avoiding collisions. However, there is a large design space to be utilized concerning tether properties such as length, damping, and elasticity. Intermediate distances of only a few hundred meters to kilometers appear best. Elasticity is not a major factor in the system's performance. Damping however, significantly improves performance, especially for non-input shaped thrust profiles. [View Full Paper]

## AAS 14 – 444

### Gravitational Actions Upon a Tether in a Non-Uniform Gravity Field With Arbitrary Number of Zonal Harmonics

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

We develop general closed-form expressions for the mutual gravitational potential, resultant and torque acting upon a rigid tethered system moving in a non-uniform gravity field produced by an attracting body with revolution symmetry, such that an arbitrary number of zonal harmonics is considered. The final expressions are series expansion in two small parameters related to the reference radius of the primary and the length of the tether, respectively, each of which are scaled by the mutual distance between their centers of mass. A few numerical experiments are performed to study the convergence behavior of the final expressions, and conclude that for high precision applications it might be necessary to take into account additional perturbation terms, which come from the mutual Two-Body interaction. [View Full Paper]

## AAS 14 – 445

### Orbital Dynamics of Large Solar Power Satellites: The Geosynchronous Laplace Plane

**Ian McNally**, School of Engineering, University of Glasgow, United Kingdom;
**Daniel Scheeres**, Colorado Center for Astrodynamics Research, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.;
**Gianmarco Radice**, School of Engineering, University of Glasgow, United Kingdom

Designs for geostationary (GEO) solar power satellites (SPS) are extremely large in scale, more than an order of magnitude larger than the International Space Station. The primary objective of the paper is to perform a detailed study of SPS orbit dynamics, obtaining a comprehensive understanding of the effect of perturbations on orbits of large SPS structures over a time-frame commensurate with proposed SPS lifetimes (30-40 years). Analytical equations derived by the process of averaging of the SPS equations of motion are used to determine the long-term orbital behavior. Previous SPS studies have simply assumed a GEO then designed control systems for maintaining it thus. It is found that an alternative SPS orbital location known as the geosynchronous Laplace plane (GLP) is superior to GEO. An SPS in GLP requires virtually no fuel to maintain its orbit, avoids the main orbital debris population originating from GEO satellites and is extremely robust, i.e. loss of control is inconsequential. The GLP SPS saves of order $10^5$ kg per year in fuel compared to a GEO SPS for equivalent power delivery. [View Full Paper]

### AAS 14 – 446

**Discretized Input Shaping for a Large Thrust Tethered Debris Object**

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

Towing objects in space has become an increasingly common concept for many missions. Asteroid retrieval, satellite servicing, and debris removal concepts often rely on a thrusting vehicle to redirect and steer a passive object. One effective way to tow the object is through a tether. This study employs a discretized tether model attached to six degree-of-freedom end bodies. To reduce the risk of a post-burn collision between the end bodies, thrust input shaping methods using continuous, discrete, and impulsive thrust profiles are considered. On-orbit simulations in a near-Earth orbit show the tethered system achieves oscillations about a gravity gradient alignment, reducing the post-burn collision likelihood. Continuous input shaping thrust profiles perform desirably, avoiding post-burn collision between the end bodies. However, they are not realistic for current day rocket engine capabilities. Impulsive input shaping profiles are considered because thrusters cannot attain continuous thrust-level modifications. Nevertheless, impulsive input shaping techniques attain similar performance by avoiding collisions and inducing gravity gradient motion of the system. [View Full Paper]

### AAS 14 – 447

**(Paper Withdrawn)**

### AAS 14 – 448

**Jovian Orbit Capture and Eccentricity Reduction Using Electrodynamic Tether Propulsion**

**Maximilian M. Schadegg** and **Ryan P. Russell**, Department of Aerospace Engineering 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.

The use of electrodynamic tethers for propulsion and power generation is attractive for missions to the outer planets, which are traditionally handicapped by large propellant requirements, large times of flight, and a scarcity of power available. In this work, the orbital dynamics of a spacecraft using electrodynamic tether propulsion during the mission phases of capture, apojove pump-down and perijove pump-up in the Jovian system are investigated. The main result is the mapped design space involving mission duration, tether length and minimum perijove radius. Phase-free flyby sequences are also included, which provide performance upper bounds for a given mission architecture. It is found to be advantageous to utilize in-bound only flybys of the Galilean moons during capture, and few, if any, out-bound only flybys during apojove pump-down. The electrodynamic tether system is also shown to be capable of lowering the spacecraft's orbit to a Europa-Ganymede Hohmann orbit with a total flight time after entering Jupiter's sphere of influence of just under two years under reasonable assumptions for spacecraft mass and tether parameters. [View Full Paper]

**AAS 14 – 449**

**Long-Term Dynamics of Fast Rotating Tethers Around Planetary Satellites**

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

We derive a semi-analytic formulation that enables the study of the long-term dynamics of fast-rotating inert tethers around planetary satellites. These equations take into account the coupling between the translational and rotational motion, which has a non-negligible impact on the dynamics, as the orbital motion of the tether center of mass strongly depends on the tether plane of rotation and its spin rate, and vice-versa. We use these governing equations to explore the effects of this coupling on the dynamics, the lifetime of frozen orbits and the precession of the plane of rotation of the tether. [View Full Paper]

**AAS 14 – 450**

**OKID as a Unified Approach to System Identification**

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

This paper presents a unified approach for the identification of linear state-space models from input-output measurements in the presence of noise. It is based on the established Observer/Kalman filter IDentification (OKID) method of which it proposes a new formulation capable of transforming a stochastic identification problem into a (simpler) deterministic problem, where the Kalman filter corresponding to the unknown system and the unknown noise covariances is identified. The system matrices are then recovered from the identified Kalman filter. The Kalman filter can be identified with any deterministic identification method for linear state-space models, giving rise to numerous new algorithms and establishing the Kalman filter as the unifying bridge from stochastic to deterministic problems in system identification. [View Full Paper]

## AAS 14 – 451

### On-Line Mass Estimation for a Tethered Space Debris During Post-Capture and Retrieval

**Fan Zhang**, Ph.D. Candidate at Northwestern Polytechnical University, Xi'an, China and Graduate Research Trainee at McGill University; **Inna Sharf** and **Arun K. Misra**, McGill University, Department of Mechanical Engineering, Montreal, Quebec, Canada

This paper presents a new methodology for on-line mass estimation for massive space debris captured by a tethered system. Mass estimation of unknown debris is critical for subsequent tasks in the space debris remediation mission, in particular, for debris retrieval and deorbiting. In the proposed algorithm, the base satellite (chaser) and space debris (target) are modeled as point masses, the latter with unknown mass. Then, the mass estimation problem is formulated and solved in two phases. First, a coarse estimate of the target mass is obtained during the post-capture phase, while the tethered system is experiencing in-plane and out-of-plane oscillations. Then, with a proper tension control scheme and the coarse estimate used as an initial guess, the debris is retrieved smoothly and a precise mass estimate is achieved. [View Full Paper]

## SESSION 27: ATTITUDE DYNAMICS AND CONTROL

**Chair: Kyle DeMars, Missouri University of Science and Technology**

## AAS 14 – 452

### External Torques Affecting the Attitude Motion of a Mercury Orbiter

**Takahiro Kato** and **Stephan Theil**, GNC Systems, Institute of Space Systems, German Aerospace Center (DLR), Bremen, Germany; **Jozef van der Ha**, Consultant, Mission Design and Operations, Bensheim, Germany

This paper investigates the attitude effects of the non-gravitational disturbances and the gravity-gradient torque on a Mercury orbiter. The harsh solar flux at Mercury induces a strong constraint on the satellite attitude orientation with respect to the Sun direction. By fixing some of the attitude pointing parameters, external disturbance torque effects can be calculated analytically. The non-gravitational disturbance models on the Mercury orbiter have been established in an analytical form, and the gravity-gradient torque effects are implemented as well. This paper defines and analyzes two Sun-constrained attitude orientations under representative orbit conditions. For the practical illustration, we employ the parameters of MESSENGER in the orbit and in the geometrical spacecraft models. Furthermore, we implement the effects of the center-of-mass offset, which drastically affect the resulting disturbance torques. Basically, the disturbance torques are governed by the gravity-gradient in the lower altitude region, the effects from the thermal re-emission on the spacecraft and the infrared planetary radiation have shown notable contributions in terms of attitude disturbances.
[View Full Paper]

## AAS 14 – 453

### Analytical Solution for Flat-Spin Recovery of Spinning Satellites

**Frank L. Janssens**, Consultant, Noordwijk, the Netherlands;
**Jozef C. van der Ha**, Consultant, Deming, Washington, U.S.A.

The paper presents new analytical and numerical results in the field of self-excited rigid-body dynamics of spinning satellites. A practical solution for a flat-spin recovery maneuver is designed and evaluated. The proposed strategy uses a continuous body- fixed torque along the minor principal axis of inertia. The motion about the torque axis is similar to a pendulum which is either oscillating (i.e., no flat-spin recovery) or revolving (i.e., successful flat-spin recovery). The transition between these two cases defines the minimum required torque level. In the case when the recovery is successful the motion within the plane normal to the torque axis describes an ellipse with continuously growing angular velocity. The results established here are of considerable practical interest for the design of spacecraft that are required to spin about their minor axes of inertia due to launcher constraints or because of specific mission requirements. [View Full Paper]

## AAS 14 – 454

### Globalstar Second Generation Hybrid Attitude Control On-Orbit Experience

**Johannes M. Hacker**, **James L. Goddard** and **Peter C. Lai**, Globalstar Inc., Milpitas, California, U.S.A.

GB2 is Globalstar's second generation communication satellite fleet manufactured by Thales Alenia Space and launched in four batches starting in October 2010. It currently consists of 24 satellites in the constellation to provide worldwide satellite phone service. The reaction wheel is one of the most reliable attitude control components in the spacecrafts. However, due to increasing demand in mission life and reaction wheel design change, reaction wheel anomalies have been increasing recently industry-wide. To extend the lifetime of the GB2 fleet, a two-wheel hybrid control algorithm was developed and successfully implemented in the satellites on orbit. The development of this control algorithm and its on-orbit experience will be presented. [View Full Paper]

## AAS 14 – 455

### Design Procedure of Chattering Attenuation Sliding Mode Attitude Control of a Satellite System

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

This study presents a design procedure for a new robust nonlinear control algorithm based on the theory of the terminal sliding mode (TSM) to control the attitude of a satellite system. Since the traditional TSM controllers include a discontinuous function, a significant problem called chattering can occur. In this paper, a methodology for designing a new switching function is discussed to alleviate this drawback over time. Besides, to highlight the robustness of the proposed method against uncertainties, a satellite with three pairs of thrusters subject to parameter variation is simulated.
[View Full Paper]

**AAS 14 – 456**
**(Paper Withdrawn)**

**AAS 14 – 457**
**(Paper Withdrawn)**

**AAS 14 – 458**
**(Paper Withdrawn)**

**AAS 14 – 459**

**Attitude Passive Stability Criteria of Axisymmetric Solar Sail Under a General Srp Model**

**Xiaosai Hu**, **Shengping Gong** and **Junfeng Li**, School of Aerospace, Tsinghua University, Beijing, China

Attitude passive stability criteria of a solar sail whose membrane surface is axisymmetric are studied in this paper under a general SRP model. This paper proved that arbitrary attitude equilibrium position can be designed through adjusting the deviation between the pressure center and the mass of the sail. Two different linearization methods are adopted to analyze the stability of the attitude equilibrium. The results show that the attitude stability depends on the membrane surface shape and area. The simulation results also confirm that the two stability criteria are almost identical for axisymmetric solar sail. Several numerical examples are presented to validate the criteria. [View Full Paper]

**AAS 14 – 460**

**Path Planning for Flexible Satellite Slewing Maneuvers: A Spectrum-Analysis-Based Approach**

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

A new path planning approach based on spectrum analysis is proposed for flexible spacecraft slewing maneuvers. First, the characteristics of traditional Bang-Coast-Bang Path and Sinusoidal Angular Acceleration path are analyzed by deriving and plotting the amplitude spectrums of the acceleration trajectories. Then, to reduce structural excitations, a modified path planning method is proposed from a frequency-domain point of view. This approach transforms the vibration reduction problem into constraints on maneuver time, maximum angular acceleration and maximum angular velocity. Finally, numerical examples are presented to validate the new method. [View Full Paper]

**AAS 14 – 461**

**CMG Momentum Management for Spacecraft in Inertial Frame**

**Mengping Zhu**, **Xinlong Chen** and **Zhi Li**, Qian Xuesen Laboratory of Space technology, China Academy of Space Technology, Beijing, China;
**Shijie Xu** and **Yue Wang**, Department of Aerospace Engineering, School of Astronautics, Beihang University, Haidian District, Beijing, P. R. China

CMG momentum management aims to slow down the accumulation of CMG momentum through active attitude adjustments. This paper discusses the momentum management problem in the inertial space which can be mainly divided into two parts: dynamics and constraints analyses and optimal controller design. In the analysis part, the required stable operating attitudes and the corresponding constraints for successful momentum management are presented. The analyses show that spacecraft with momentum management are required to keep one of their principal axes of inertia perpendicular to the orbital plane. Due to the uncertainty of the inertia property, the requirement of absolute perpendicularity is difficult to realize. To solve this problem, the second part of the paper presents an optimal momentum management controller, where CMG momentum is feedback controlled to avoid momentum accumulation. Theoretical analyses and simulation results show that the CMG momentum oscillates periodically under the impact of gravitational and aerodynamic torque with no significant growth in the magnitude when managed in the inertial space. [View Full Paper]

**AAS 14 – 462**
**(Paper Withdrawn)**

**AAS 14 – 463**
**(Paper Withdrawn)**

## SESSION 28: LUNAR MISSION DESIGN
### Chair: Jeffrey Parker, University of Colorado

**AAS 14 – 464**

**Orbit Design Considerations for Precision Lunar Landing for a Sample Return Mission**

**Zhong-Sheng Wang**, **Zhanfeng Meng**, **Shan Gao** and **Jing Peng**, China Academy of Space Technology, China Space, Haidian District, Beijing, P. R. China;
**Adly L. Espinoza**, Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.

A lunar lander for a sample return mission achieves a circular orbit after the lunar orbit insertion maneuvers. It is demonstrated in this paper that a two-by-two targeting maneuver plus a phasing maneuver or an orbit plane change maneuver can be used to achieve the precision landing on the lunar surface. It is essential to use a descent dynamic model with high fidelity and have accurate information of the guidance law used during the powered descent. Also demonstrated is an orbit design technique that uses the tracking condition as a natural time reference in planning the maneuvers.
[View Full Paper]

**AAS 14 – 465**

**Some Options for Lunar Exploration Utilizing the Earth-Moon L2 Libration Point**

**David W. Dunham**, Space Navigation and Flight Dynamics, KinetX, Inc., Greenbelt, Maryland, U.S.A.;
**Robert Farquhar**, Space Navigation and Flight Dynamics, KinetX, Inc., Burke, Virginia, U.S.A.;
**Natan Eismont**, Space Research Institute, Moscow, Russia;
**Eugene Chumachenko**, **Sergey Aksenov**, **Yulia Fedorenko**, **Yulia Nikolaeva**, **Ekaterina Efremova** and **Pavel Krasnopolski**, Mechanics and Mathematical Simulation, National Research University "Higher School of Economics," Moscow, Russia;
**Roberto Furfaro** and **John Kidd, Jr.**, Department of Systems and Industrial Engineering, University of Arizona, Tucson, Arizona, U.S.A.

The Moon is a logical next step for human exploration beyond low-Earth orbit. The lunar far side remains unexplored by landed spacecraft. From Earth-Moon L2 libration-point orbits, astronauts could operate robotic spacecraft on the lunar farside. Such orbits can also be used as transportation nodes for reaching more distant destinations. We investigate low deltaV trajectories that simply loop around L2, spending nearly two weeks over the lunar back side. Also investigated are the occultation times for Earth ground stations for Lissajous orbits of different sizes, and the deltaV costs to reach and return from such orbits. [View Full Paper]

## AAS 14 – 466

### Study of Gravitational Lunar Capture in the Bi-Circular Problem

**Yi Qi** and **Shijie Xu**, Department of Astronautics, Beihang University, Haidian District, Beijing, P. R. China; **Rui Qi**, Department of Aerospace Engineering, Beijing Insitute of Technology, Haidian District, Beijing, P. R. China; **Yue Wang**, Department of Astronautics, Beihang University, Haidian District, Beijing, P. R. China

Gravitational capture is a useful phenomenon in the design of the low energy transfer (LET) orbit for a space mission. In this paper, gravitational lunar capture based on the Sun-Earth-Moon bi-circular model (BCM) in restricted four body problem (R4BP) is studied. By the mechanics analysis in the space near the Moon, we introduce a new parameter *k*, the corrected ratio of the radial force, to investigate the influence of radial force on the capture eccentricity in the BCM. Then the parametric analysis is performed to detect the influences on the corrected ratio *k*. Considering the restriction of time-of-flight and corrected ratio, we investigate respectively the minimum capture eccentricity and the corrected minimum capture eccentricity. Via numerical analysis, we discover two special regions on the sphere of capture, in which the capture point possesses the global minimum capture eccentricity and corrected capture eccentricity. It denotes the optimal effect of the gravitational capture. In addition, the entrance points of the gravitational capture on the sphere of influence are also studied by numerical methodology. According to the results obtained, some suggestions on the design of the LET orbit are given. [View Full Paper]

## AAS 14 – 467

### Various Transfer Options From Earth into Distant Retrograde Orbits in the Vicinity of the Moon

**Lucía Capdevila**, **Davide Guzzetti** and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.

Future applications within the Earth-Moon neighborhood, under a variety of mission scenarios, such as NASA's Asteroid Redirect Robotic Mission (ARRM), may exploit lunar Distant Retrograde Orbits (DROs). Thus, further investigation of transfers to and from these orbits is useful. The current study is focused on transfer trajectory options that employ impulsive maneuvers to deliver a vehicle from Low Earth Orbit (LEO) into various lunar DROs. The stability region surrounding specific DROs, as modeled in the Earth-Moon Circular Restricted Three-Body Problem (CR3BP), may also serve to facilitate the transfer design process and is explored within that context. Representative solutions are transitioned to an ephemeris model and station keeping costs are compared. [View Full Paper]

## AAS 14 – 468

### Low-Energy Escape from the Sun-Earth L2 Halo Orbit Utilizing Unstable Manifolds and Lunar Gravity Assist

**Hongru Chen**, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka, Japan; **Yasuhiro Kawakatsu**, Department of Space Flight Systems, ISAS/JAXA, Sagamihara, Kanagawa, Japan; **Toshiya Hanada**, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka, Japan

The paper investigates the escape strategy using the unstable manifolds of the Sun-Earth $L_2$ halo orbit and lunar gravity assist. There are four cases of intersection of the manifold tubes associated with halo orbits and the orbit of the Moon. The four intersections have different $V_\infty$ with respect to the Moon. The corresponding lunar gravity assists can result in a range of escape trajectories, granting choices for the extended mission of halo orbits. In order to satisfy the lunar encounter requirements, the strategy and $\Delta V$ costs of phasing maneuvers are presented as well. [View Full Paper]

## AAS 14 – 469

### Design of Lunar Free-Return Trajectories Based on UKF Parameter Estimation

**Hongli Zhang**, School of Astronautics, Beihang University, Haidian District, Beijing, P. R. China; **Qinqin Luo**, Beijing Aerospace Technology Institute, Haidian District, Beijing, P. R. China; **Jianfeng Yin**, China Academy of Space Technology (CAST), Fengtai District, Beijing, China; **Chao Han**, School of Astronautics, Beihang University, Haidian District, Beijing, P. R. China

A new algorithm based on unscented Kalman filter (UKF) parameter estimation for the fast and efficient design of lunar free-return trajectories is proposed. The initial estimate of the free-return trajectory is generated under the two-body model. Then the original design problem is converted to a parameter estimation problem. Through solving the problem using UKF, the converged exact solution is found. Compared with the traditional differential-correction method, the derivation of the gradient matrix is not required and a much larger convergence domain is obtained. Numeric examples are implemented to examine the reliability and efficiency of the algorithm. [View Full Paper]

## AAS 14 – 470

### Trade-Off Between Cost and Time in Lunar Transfers: A Quantitative Analysis

**Francesco Topputo**, Department of Aerospace Science and Technology, Politecnico di Milano, Milan, Italy.

In this paper, two-impulse Earth–Moon transfers are studied in a four-body model. For given departure, arrival orbits, the focus is on reconstructing the total set of possible solutions within a specified maximum transfer time. This is done by formulating the transfer as a nonlinear programming problem, and by solving it with direct transcription and multiple shooting. The outcome is analyzed in a cost vs. transfer time plane, where orbits showing their best balance are studied. With this approach, Hohmann, interior, and exterior transfers, as well as the existing literature, can be viewed as special points of a more general picture, where new solutions emerge. [View Full Paper]

## AAS 14 – 471

### Families of Solar-Perturbed Moon-to-Moon Transfers

**Gregory Lantoine** and **Timothy P. McElrath**, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

In the modern space era, the Moon is now considered as a gateway to deep space, and the ability to design multiple lunar flybys is therefore becoming increasingly important. In this paper, to provide quick estimates of lunar flyby trajectories, we compute, characterize and classify families of solar-perturbed Moon-to-Moon transfers in the Sun-Earth three-body problem. These families are obtained by continuation on the initial lunar relative velocity and the angle between the first lunar flyby location and the solar direction. Practical use of the families to design double and triple lunar flybys is also demonstrated. [View Full Paper]

## AAS 14 – 472

### Establishing a Network of Lunar Landers Via Low-Energy Transfers

**Jeffrey S. Parker**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.

Low-energy trajectories have been found to offer an incredibly flexible architecture for placing multiple landers on the surface of the Moon using a single launch. The low-energy architecture makes it possible to place each lander anywhere on the surface – the near side or the far side – such that it lands in the local morning. Each lander requires only small course adjustments before landing: the landing itself is the only large maneuver. This feature permits the landers to be designed using simplified propulsion systems, such as solid rocket motors and monopropellant systems, which improves the value of each lander. [View Full Paper]

**AAS 14 – 473**

**A Navigator's Journey (Abstract and Biography Only)**

**Robert H. Bishop**, Dean of Engineering, Marquette University, Milwaukee, Wisconsin, U.S.A.

The tale of a professor's program of research and teaching is told through the stories of the people, programs, and places stretching across time from early Space Shuttle rendezvous missions to plans for precision fast-to-flight entry, descent, and landing navigation with hazard detection and avoidance. Central to the story is the Kalman filter. The fundamental linear Kalman filter equations are well known with stability and performance guarantees under the assumptions of the underlying theory. The reality of nonlinearities, model uncertainties, measurement errors with unknown or undesirable noise characteristics, and other deviations from the linear theory transform the implementation of practical navigation algorithms based on the Kalman filter to an exercise of blending theory and art that leads to fascinating teaching opportunities within a rigid research environment. This short talk will highlight the link between practical estimation algorithms and methods as applied to on-orbit relative navigation in the early Space Shuttle era and the more complex entry, descent, and landing navigation challenges posed by the Morpheus vehicle, and how NASA missions influenced one professor's ambition to inspire students to explore. [View Full Summary]

# Author Index