SPACEFLIGHT MECHANICS 2011

Front Cover Illustration:

This is one segment of an infrared portrait of dust and stars radiating in the inner Milky Way. More than 800,000 frames from NASA's Spitzer Space Telescope were stitched together to create the full image, capturing more than 50 percent of our entire galaxy.

This is a three-color composite that shows infrared observations from two Spitzer instruments. Blue represents 3.6-micron light and green shows light of 8 microns, both captured by Spitzer's infrared array camera. Red is 24-micron light detected by Spitzer's multiband imaging photometer. This combines observations from the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) and MIPSGAL projects.

Image Credit: NASA/JPL-Caltech/University of Wisconsin.

SPACEFLIGHT MECHANICS 2011

Volume 140

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Moriba K. Jah
Yanping Guo
Angela L. Bowes
Peter C. Lai

Proceedings of the 21st AAS/AIAA Space Flight Mechanics Meeting held February 13-17, 2011, New Orleans, Louisiana.

Published for the American Astronautical Society by
Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

First Printing 2011

Library of Congress Card No. 57-43769

ISSN 1081-6003

ISBN 978-0-87703-569-5 (Hard Cover Plus CD ROM)
ISBN 978-0-87703-570-1 (CD ROM Version)

Published for the American Astronautical Society
by Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

Printed and Bound in the U.S.A.

CONTENTS

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

FOREWORD

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

Spaceflight Mechanics 2011, Volume 140, Advances in the Astronautical Sciences, consists of three parts totaling about 2,622 pages, plus a CD ROM which contains all the available papers in digital format. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume. A chronological index and an author index are appended to the third part of the volume.

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

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

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

Spaceflight Mechanics 2011 appears as Volume 140, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the 21st AAS/AIAA Space Flight Mechanics Meeting 2011.

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 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

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

Robert H. Jacobs, Series Editor

PREFACE

The 21st Space Flight Mechanics Meeting was held at the Loews New Orleans Hotel, New Orleans, Louisiana, on February 13-17, 2011. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 192 people registered for the meeting. Attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

There were 152 technical papers presented in 25 sessions on topics related to spaceflight mechanics and astrodynamics, including 2 special sessions on Optical Navigation and Innovative G&C Test Solutions and a special topic on NASA Decadal Survey Studies. A Dirk Brouwer Award Plenary was held on Wednesday afternoon and the 2011 AAS Dirk Brouwer Award recipient, Donald Kessler, presented a lecture on orbital debris. The meeting included 4 social events. The Early Bird Reception took place during the evening of February 13 at the Loews Hotel and was an opportunity for attendees to meet and catch up with everyone. The Student and Young Professional Reception took place during the evening of February 14 at the Loews Hotel. It was sponsored by Texas A&M University and allowed students and young attendees to enjoy some food and see information about Texas A&M's program. An offsite event at the Musée Conti Wax Museum in the French Quarter on February 15 included dinner and drinks for attendees wishing to relax and see a bit of New Orleans. Finally, a farewell "Happier Hour" took place at the Loews Hotel on February 16.

The editors extend their gratitude to the Session Chairs who made this meeting successful: Dr. Xiaoli Bai, Dr. Matthew Berry, Dennis Byrnes, Dr. Thomas Eller, Dr. Kathleen Howell, Dr. Austin Lee, Dr. Thomas Lovell, Dr. Don Mackison, Dr. Craig McLaughlin, Dr. Daniele Mortari, Dr. William Owen, Dr. Ryan Park, Lisa Policastri, Dr. Chris Ranieri, Dr. Ryan Russell, John Seago, Jon Sims, Dr. David Spencer, Dr. Thomas Starchville, Dr. Sergei Tanygin, Dr. Aaron Trask, Al Treder, Dr. Robin Vaughan, Dr. Matthew Wilkins, Renato Zanetti, and Dr. Zhiqiang Zhou. Our gratitude also goes to Dr. Shannon Coffey for his support and assistance with website administration.

We would also like to express our thanks to The Aerospace Corporation for the cover design, printing, and shipping of the conference programs.

AAS Technical Chair
Dr. Moriba Jah
AFRL/RVSV

AAS General Chair
Angela Bowes
AMA, Inc./NASA LaRC

AIAA Technical Chair
Dr. Yanping Guo
Johns Hopkins University APL

AIAA General Chair
Dr. Peter C. Lai
The Aerospace Corporation

PAPERS BY NUMBER AND TITLE

VOLUME 140 I, II & III

ADVANCES IN THE ASTRONAUTICAL SCIENCES,
SPACEFLIGHT MECHANICS 2011 (2011)

(AAS/AIAA Astrodynamics Specialist Conference, February 13-17, 2011, New Orleans, Louisiana, U.S.A.)

SESSION 1: ASTEROID MISSIONS I

AAS 11 – 100	A Mission Analysis Survey of Potential Human-Precursor Robotic Asteroid Missions, Michael L. Cupples, Roberto Furfaro, Carl W. Hergenrother, Badejo O. Adebonojo Jr., Daniel R. Wibben and John N. Kidd Jr.
AAS 11 – 101	(Paper Withdrawn)
AAS 11 – 102	Human Exploration of Near-Earth Asteroids Via Solar Electric Propulsion, Damon Landau and Nathan Strange
AAS 11 – 103	Applications of an Ares V-Class HLV for Robotic NEO Deflection Missions, Dan Zimmerman, Sam Wagner and Bong Wie
AAS 11 – 104	Dynamics of Levitating Dust Particles Near Asteroids and the Moon, Christine M. Hartzell and Daniel J. Scheeres
AAS 11 – 105	(Paper Withdrawn)
AAS 11 – 106	Sequential Shape Estimation of an Asteroid Using Vision, Neha Satak, Manoranjan Majji and John E Hurtado
AAS 11 – 107	The Extended Gravity-Tractor: An Alternative to Improve Asteroid Towing Merits, Dario O. Cersosimo
AAS 11 – 108	(Paper Withdrawn)

SESSION 2: ATTITUDE DYNAMICS AND CONTROL I

AAS 11 – 109	Attitude Motion of a Spinning Spacecraft With Fuel Sloshing and Nutation Damping, Mohammad A. Ayoubi, Farhad A. Goodarzi and Arun Banerjee
AAS 11 – 110	First Flight Results on Time-Optimal Spacecraft Slews, M. Karpenko, N. Bedrossian, S. Bhatt, A. Fleming and I. M. Ross
AAS 11 – 111	High Fidelity Simulation of Swampsat Attitude Determination and Control System, Josue D. Muñoz, Vivek Nagabhushan, Sharan Asundi and Norman G. Fitz-Coy
AAS 11 – 112	Modeling of Attitude Dynamics for Ikaros Solar Sail Demonstrator, Yuichi Tsuda, Takanao Saiki, Yuya Mimasu and Ryu Funase
AAS 11 – 113	(See Session 24)

SESSION 3: ORBIT DETERMINATION

SESSION 4: TRAJECTORY DESIGN AND OPTIMIZATION I

SESSION 8: TRAJECTORY DESIGN AND OPTIMIZATION II

SESSION 9: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL

SESSION 10: ORBITAL DEBRIS AND SPACE ENVIRONMENT

SESSION 11: ASTEROID MISSIONS II

SESSION 12: DECADAL SURVEY AND INTERPLANETARY MISSION DESIGN

AAS 11 – 188 Conceptual Mission Design of a Polar Uranus Orbiter and Satellite Tour, James McAdams, Christopher Scott, Yanping Guo, John Dankanich and Ryan Russell

AAS 11 – 189 Interplanetary Electric Propulsion Uranus Mission Trades Supporting the Decadal Survey, John W. Dankanich and James Mcadams

AAS 11 – 190 Interplanetary Trajectory Design of Space Vehicle With Bimodal Nuclear Propulsion, Oleksandr Dekhtiar and Oleksii Kharytonov

AAS 11 – 191 Jupiter Trojan Orbiter Mission Design Trades Supporting the Decadal Survey, John W. Dankanich and James McAdams

AAS 11 – 192 Trajectory Design of Solar Orbiter Using Earth and Venus Gravity Assists, José M. Sánchez Pérez

AAS 11 – 193 (Paper Withdrawn)

SESSION 13: SPECIAL SESSION: INNOVATIVE GNC TEST SOLUTIONS

AAS 11 – 194 Attitude Sensors' Miniaturization Facilitates Optimization of Testing Activities, P. Fidanzati, F. Boldrini, E. Monnini and P. Airey

AAS 11 – 195 Control Design for a Six Degree-of-Freedom Shaker, Walter H. Chung, Allen Raines and John Shishido

AAS 11 – 196 Development of a Fine Track System for the Aerospace Laser Communications Testbed, Jason C. Cardema, Charles M. Klimcak and Alinn R. Herrera

AAS 11 – 197 Architecture for Unconstrained 3-Axis Attitude Determination and Control Test Bed, Vivek Nagabhushan, Shawn Allgeier and Norman G. Fitz-Coy

AAS 11 – 198 Full Performance Testing of Autonomous Star Sensors Under Laboratory Environment, Uwe Schmidt, Boris Pradarutti and Klaus Michel

AAS 11 – 199 HYDRA Star Tracker Innovative Test Solution, Yves Kocher, Benoit Gelin, Damien Piot, Frédéric Gorog and Ludovic Blarre

AAS 11 – 200 (Paper Withdrawn)

SESSION 14: ORBIT DETERMINATION AND NAVIGATION

AAS 11 – 201 A Splitting Gaussian Mixture Method for the Propagation of Uncertainty in Orbital Mechanics, Kyle J. DeMars, Robert H. Bishop and Moriba K. Jah

AAS 11 – 202 Analytical Non-Linear Propagation of Uncertainty in the Two-Body Problem, K. Fujimoto, D. J. Scheeres and K. T. Alfriend

AAS 11 – 203 Estimating a High-Resolution Lunar Gravity Field and Time-Varying Core Signature, Ryan S. Park, Sami W. Asmar, Eugene G. Fahnestock, Alex S. Konopliv, Wenwen Lu and Mike M. Watkins

AAS 11 – 204 (Paper Withdrawn)

AAS 11 – 205 Modification of Atmospheric Mass Density Model Coefficients Using Space Tracking Data – A Simulation Study for Accurate Debris Orbit Prediction, Jizhang Sang, Craig Smith and Kefei Zhang

AAS 11 – 206 (Paper Withdrawn)

SESSION 18: LOW-THRUST TRAJECTORY DESIGN

SESSION 19: EARTH ORBIT AND MISSIONS

SESSION 20: DYNAMICAL SYSTEMS AND ORBITAL MECHANICS

SESSION 21: SPACE DEBRIS REMOVAL

SESSION 22: ATTITUDE SENSOR

SESSION 23: TRAJECTORY AND MISSION ANALYSIS

SESSION 24: ATTITUDE DYNAMICS AND CONTROL II

SESSION 25: LUNAR TRAJECTORY DESIGN

DIRK BROUWER AWARD PLENARY LECTURE

SESSION 1: ASTEROID MISSIONS I
Chair: Dennis Byrnes, Jet Propulsion Laboratory

AAS 11 – 100

A Mission Analysis Survey of Potential Human-Precursor Robotic Asteroid Missions

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

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

AAS 11 – 101
(Paper Withdrawn)

AAS 11 – 102

Human Exploration of Near-Earth Asteroids Via Solar Electric Propulsion

Damon Landau, Outer Planet Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.;
Nathan Strange, Mission Systems Concepts, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

There have been many proposed technologies and architectures to extend a human presence beyond the Moon. Solar electric propulsion (SEP) provides the capability to implement a wide variety of missions with relatively low injected mass to low-Earth orbit. Because of its broad applicability this technology can enable progressively ambitious steps towards Mars by incrementally increasing power. The benefits of SEP are addressed for cis-lunar excursions, near-Earth asteroid exploration, and missions to Phobos and Deimos, and compared to chemical propulsion and nuclear thermal technologies. In particular, SEP expands the range of near-Earth asteroids accessible with a constrained launch capability (IMLEO). [View Full Paper]

AAS 11 – 103

Applications of an Ares V-Class HLV for Robotic NEO Deflection Missions

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

This study examines near-Earth object (NEO) deflection missions employing an Ares V-class heavy launch vehicle (HLV). The missions utilize high energy deflection methods involving various nuclear explosion variants, which are capable of fragmenting or ablating a potentially hazardous NEOs. Three different types of detonation options are also examined for each terminal phase scenario. The asteroid Apophis is used as a baseline to demonstrate mission design and system architecture examples in the 2029 to 2036 time frame. This study shows that with the capabilities of an Ares V-class HLV, nearly continuous launch windows exist for rendezvous and direct intercept missions. To help illustrate the performance advantages that an Ares V-class HLV could have to NEO deflection missions, the Delta IV-H launch vehicle is used in a comparison study. It is shown that the Delta IV-H launch vehicle is extremely inadequate for the types of deflection missions examined in this study. [View Full Paper]

AAS 11 – 104

Dynamics of Levitating Dust Particles Near Asteroids and the Moon

Christine M. Hartzell and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

The movement of small dust particles near the surface of the Moon and asteroids due to electrostatic forces is being investigated to explain several observational phenomena. However, to date, a feasible method for launching particles off the surface of these bodies has not been described. Thus, existing numerical models of dust transport use arbitrarily chosen initial particle states. From numerical models, we see that a subset of particles experience altitude oscillations above the body's surface rather than traditional conic orbits. It is possible that dust particles released from the surface during exploration activities could levitate as well. The equations of motion of this system are coupled and the motion is nonconservative. We have numerically calculated the equilibria of the system and developed an analytical approximation of the stable equilibria. The stability of the equilibria are evaluated both for the linearized system and the fully nonlinear system. By understanding the behavior of particles near the stable equilibria, it will then be possible to state whether or not particle levitation occurs naturally (once a feasible particle launching method is identified) or due to exploration activities.
[View Full Paper]

AAS 10 – 105
(Paper Withdrawn)

AAS 11 – 106

Sequential Shape Estimation of an Asteroid Using Vision

Neha Satak, **Manoranjan Majji** and **John E. Hurtado**, Department of Aerospace Engineering, Texas A& M University, College Station, Texas, U.S.A.

Proximity operations require accurate gravity and shape model of an asteroid. A method for reconstructing the shape model is by using photographic measurements. Tracking surface-features in successive image pairs enable the reconstruction of the asteroid. At close proximity the imaging spacecraft experiences large perturbations due to gravitational harmonics of the asteroid. We develop a methodology to design optimal imaging orbits about an arbitrary asteroid. While the method starts from an ellipsoidal approximation, the shape model of the asteroid is continuously updated for calculating intermediate differential thrust corrections. [View Full Paper]

AAS 11 – 107

The Extended Gravity-Tractor:
An Alternative to Improve Asteroid Towing Merits

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

The extended gravity-tractor (xGT) concept is derived from the well-known gravity-tractor (GT). The xGT is intended to improve the towing performance of the classical GT by taking into consideration the shape and rotational state of a generic asteroid. The xGT hovering strategy consists on guiding the spacecraft towards and away the NEO's center of mass along the towing vector. This motion is synchronized with the asteroid spin, consequently increasing the gravitational pull on the NEO. A first-order analysis using a two-body model found the xGT could improve towing merits up to 50% over the classical GT, thus reducing towing times. [View Full Paper]

AAS 10 – 108
(Paper Withdrawn)

SESSION 2: ATTITUDE DYNAMICS AND CONTROL I
Chair: Dr. Robin Vaughan, JHU Applied Physics Laboratory

AAS 11 – 109
Attitude Motion of a Spinning Spacecraft with Fuel Sloshing and Nutation Damping

Mohammad A. Ayoubi and **Farhad A. Goodarzi**, Department of Mechanical Engineering, Santa Clara University, Santa Clara, California, U.S.A.; **Arun Banerjee**, Lockheed Martin Advanced Technology Center, Palo Alto, California, U.S.A.

We use Kane's method to present the equations of motion of a spinning spacecraft with three momentum wheels, a nutation damper, and a spherical pendulum. The spherical pendulum is adopted as a simple mechanical equivalent of fuel sloshing in partially-filled tanks. The proposed model is an extension of the existing model in the literature. We verify and validate our model for two cases: flat spin and a simple reorientation maneuver. Numerical simulations are in agreement with existing results in the literature. The results confirm the accuracy of the model for a typical spacecraft.
[View Full Paper]

AAS 11 – 110
First Flight Results on Time-Optimal Spacecraft Slews

M. Karpenko and **I. M. Ross**, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, California, U.S.A.; **N. Bedrossian**, **S. Bhatt**, The Charles Stark Draper Laboratory, Houston, Texas, U.S.A.; **A. Fleming**, Leffler Consulting, LLC, Chantilly, Virginia, U.S.A.

This paper describes the design and flight implementation of off-eigenaxis time-optimal reorientation maneuvers for the NASA Transition Region and Coronal Explorer (TRACE) spacecraft. Time-optimal reorientation maneuvers have obvious application for improving the maneuver performance of spacecraft systems. Yet, this type of maneuvering capability has never before been demonstrated in flight. Constrained time-optimal maneuvering of a rigid body is studied first in order to demonstrate the potential for enhancing the performance of the TRACE spacecraft. Issues related to the experimental flight implementation of time-optimal maneuvers on board TRACE are discussed. A description of an optimal control problem formulation found to be suitable for reaction wheel spacecraft maneuver design is given. The optimization model is solved using the pseudospectral optimal control method and includes practical constraints such as the nonlinear reaction wheel torque-momentum envelope and rate gyro saturation limits. Flight results, presented for a typical large angle time-optimal reorientation maneuver, show that time-optimal maneuvers can be implemented without any modification of the existing spacecraft attitude control system and demonstrate a clear improvement in spacecraft maneuver performance as compared to conventional eigenaxis maneuvering. [View Full Paper]

AAS 11 – 111

High Fidelity Simulation of SwampSat Attitude Determination and Control System

Josue D. Muñoz, **Vivek Nagabhushan**, **Sharan Asundi** and **Norman G. Fitz-Coy**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.

The development of a high fidelity model of SwampSat's attitude determination and control system is presented. The spacecraft model includes detailed actuator and sensor models which are based on actual hardware characterization tests and/or manufacturer specifications for the COTS components. The model also includes a high fidelity treatment of the spacecraft environmental disturbances. Simulation results for the SwampSat mission are presented and discussed. [View Full Paper]

AAS 11 – 112

Modeling of Attitude Dynamics for IKAROS Solar Sail Demonstrator

Yuichi Tsuda, **Takanao Saiki** and **Ryu Funase**, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan; **Yuya Mimasu**, Department of Aeronautics and Astronautics, Kyushu University, Fukuoka, Japan

This paper describes a method of modeling attitude dynamics of spinning solar sail spacecraft under influence of solar radiation pressure (SRP). This method is verified and actually exploited in the operation of Japanese interplanetary solar sail demonstration spacecraft IKAROS. IKAROS shows a unique attitude behavior due to strong SRP effect. This paper shows a new attitude model of spinning sail, which is verified by flight data of IKAROS. It is also shown that the model proposed in this paper has a direct relation with the Generalized Sail Model. [View Full Paper]

AAS 11 – 113

(See Session 24)

AAS 11 – 114

Relative Attitude Determination from Planar Vector Observations

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

A method for relative attitude determination from planar line-of-sight observations is presented. Three vehicles are assumed to be equipped with sensors to provide measurements of the three inter-vehicle line-of-sight vectors. The line-of-sight vectors are further assumed to be always in the same plane. This information is combined with all the available measurements to find an optimal relative attitude estimation solution. Covariance analysis is provided to help gain insight on the statistical properties of the attitude errors of the solution. [View Full Paper]

AAS 11 – 115

Rigid-Body Attitude Tracking with Vector Measurements and Unknown Gyro Bias

Travis H. Mercker and **Maruthi R. Akella**, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.

The problem of rigid-body attitude tracking is examined for the case where there is an unknown gyro-bias and vector attitude measurements are used which necessitate estimation of the attitude quaternion. A new adaptive control scheme is proposed that meets the attitude tracking control objective of forcing the attitude and angular velocity tracking errors to zero by a suitable re-parameterization of the unknown gyro-bias parameters. In addition, it is shown that the bias and the quaternion estimates converge to their corresponding true values irrespective of the nature of the underlying attitude reference trajectory. Controllers are introduced for the cases where the body's inertia matrix is both known and unknown. Convergence is shown through a Lyapunov-like stability analysis, and performance of the controllers is shown through simulation. Furthermore, simulations are shown with noise on the available measurements and with slowly varying gyro-bias to highlight the performance benefits of the proposed control scheme.
[View Full Paper]

SESSION 3: ORBIT DETERMINATION

Chair: Dr. Craig McLaughlin, University of Kansas

AAS 11 – 116

A Comprehensive Comparison Between Angles-Only Initial Orbit Determination Techniques

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

During the last two centuries many methods have been proposed to solve the angles-only initial orbit determination problem. Initial orbit determination remains necessary to provide an estimate for high accuracy orbit determination and as such, it is important to perform direct comparisons among the popular methods with the aim of determining which methods are the most suitable (accuracy, robustness) for different orbit determination scenarios. The orbit error is here quantified by two new general orbit error parameters identifying the capability to capture the orbit shape and the orbit orientation. The study concludes that for nearly all but a few cases, the Gooding method best estimates the orbit. [View Full Paper]

AAS 11 – 117

Distributed Orbit Determination Via Estimation Consensus

Ran Dai, **Unsik Lee** and **Mehran Mesbahi**, Department of Aeronautics and Astronautics, University of Washington, Seattle, Washington, U.S.A.

This paper proposes an optimal algorithm for distributed orbit determination by using discrete observations provided from multiple tracking stations in a connected network. The objective is to increase the precision of estimation by communication and cooperation between tracking stations in the network. We focus on the dynamical approach considering a simplified Low Earth Orbital Satellite model with random perturbations introduced in the observation data which is provided as ranges between tracking stations and satellite. The dual decomposition theory associated with the subgradient method is applied here to decompose the estimation task into a series of suboptimal problems and then solve them individually at each tracking station to achieve the global optimality. [View Full Paper]

AAS 11 – 118

ICESat Precision Orbit Determination Experiments at Low Altitude

Hyung-Jin Rim, **Sungpil Yoon** and **Bob E. Schutz**, Center for Space Research, University of Texas at Austin, Austin, Texas, U.S.A.

ICESat was decommissioned in 2010 and the orbit was lowered from 600 km altitude to hasten reentry, which occurred on August 31, 2010. The ICESat Black-Jack GPS receiver was operated until August 14 when the perigee altitude was about 200 km. Precision orbit determination experiments were conducted with the GPS data and with ground-based laser ranging data through August 14. Preliminary POD experiments at the low altitude using updated parameterizations and models have produced daily solutions, which result in satellite laser range residuals of about 3 cm, compared with about 2 cm produced by the POD at 600 km. [View Full Paper]

AAS 11 – 119

Improved Orbit Determination Using Second-Order Gauss-Markov Processes

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

Confronted with fundamental uncertainties regarding orbital system dynamics and given the abundance of tracking data from GPS, the estimation of empirical accelerations has become standard practice in precise orbit determination (POD) of near-Earth satellites. In sequential filtering an exponentially time-correlated system noise process is typically postulated, corresponding to a first-order Gauss-Markov process (GMP). In the present work we address the possibility of using second-order GMP in POD. Improvements are demonstrated for sparse and intermittent tracking as well as for orbit predictions at unobserved future epochs, in terms of both more accurate states and more realistic covariance envelopes. [View Full Paper]

AAS 11 – 120

Meteosat Orbit Determination Using Starbrook Optical Directional Observations

Milan Klinc and **David Lázaro**, Operations Department, consultants at EUMETSAT, Darmstadt, Germany

An enhanced orbit determination method, combining standard ranging data with optical directional observations, was tested at EUMETSAT. The method combined measurements taken by a wide field of view space surveillance sensor (Starbrook) with EUMETSAT's own ground segment ranging data. The aim was to obtain an ideal match between the optical sensor detection capabilities, which are optimized for a general surveillance role, and keeping minimal the required processing software sophistication at the control centre, to form a suitable system for use in routine Meteosat orbit determination. The results obtained during a trial period between March and June 2010 demonstrated the validity of the concept and its considerable potential for direct application to routine operations. [View Full Paper]

AAS 11 – 121

On Laplace's Orbit Determination Method: Some Modifications

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

Three modifications towards enhancing the accuracy and performance of Laplace's method of orbit determination are presented. In the main procedure of the algorithm, an eighth order polynomial needs to be solved for each iteration as the middle range gets corrected. Also an initial guess is required to start the iteration and the correct root should be chosen with care. The first modification presented in this work completely eliminates the polynomial root solving procedure and the trivial initial guess of zero can be used to start the iteration. In the second modification, the first and second time derivatives of the middle range is approximated by the other ranges so all three ranges (if three observations) can be determined by solving just one system of equation which is the basis of the next algorithm improvement based on which the singularity associated with Laplace's method for the coplanar cases will be removed. To handle the coplanar scenarios, at least four observations would be required. Also multiple observations can be used with the modified algorithm to increase the accuracy. All multiple ranges can be determined at the same time while the original Laplace's method estimates just one unknown range at a time. [View Full Paper]

AAS 11 – 122

(Paper Withdrawn)

AAS 11 – 123

Sequential Orbit-Estimation With Sparse Tracking

John H. Seago and **James W. Woodburn**, Analytical Graphics Inc., Exton, Pennsylvania, U.S.A.; **Jacob Griesbach**, Analytical Graphics Inc., Colorado Springs, Colorado; **David A. Vallado**, Center for Space Standards and Innovation, Colorado Springs, Colorado

A properly initialized sequential orbit estimator will converge to less certain state estimates whenever the density of the spacecraft tracking is relatively low; nevertheless, these estimates should remain viable as long the estimator's working assumptions are met. However, when tracking data are sparse, violations of certain working assumptions may pose special problems, such as when outliers exist. In this paper, some mitigation strategies are explored for such cases and these are contrasted with typical batch-least-squares techniques, with the observation that a sequential orbit estimator presents it own benefits whenever tracking data are sparsely distributed.
[View Full Paper]

SESSION 4: TRAJECTORY DESIGN AND OPTIMIZATION I

Chair: Dr. Ryan Russell, Georgia Institute of Technology

AAS 11 – 124

Direct Method Transcription for a Human-Class Translunar Injection Trajectory Optimization

Kevin E. Witzberger, Mission Design and Analysis Branch, NASA Glenn Research Center, Cleveland, Ohio, U.S.A.; **Dr. Tom Zeiler**, Aerospace Engineering and Mechanics Department, The University of Alabama, Tuscaloosa, Alabama

This paper presents a new trajectory optimization software package developed in the framework of a low-to-high fidelity three degree-of-freedom (3-DOF)/6-DOF vehicle simulation program named Mission Analysis Simulation Tool in Fortran (MASTIF) and its application to a translunar trajectory optimization problem. The functionality of the developed optimization package is implemented as a new "mode" in generalized settings to make it applicable for a general trajectory optimization problem. In doing so, a direct optimization method using collocation is employed for solving the problem. Trajectory optimization problems in MASTIF are transcribed to a constrained nonlinear programming (NLP) problem and solved with SNOPT, a commercially available NLP solver. A detailed description of the optimization software developed is provided as well as the transcription specifics for the translunar injection (TLI) problem. The analysis includes a 3-DOF trajectory TLI optimization and a 3-DOF vehicle TLI simulation using closed-loop guidance. [View Full Paper]

AAS 11 – 125

Flyby Design Using Heteroclinic and Homoclinic Connections of Unstable Resonant Orbits

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

Tour designs using flybys have traditionally been studied using two-body patched conic methods. Previous work has shown that trajectories designed using these techniques and with optimization methods follow the invariant manifolds of unstable resonant orbits as they transition between resonances. This work is continued here by computing heteroclinic and homoclinic trajectories associated with these unstable resonant orbits. These trajectories are used with multiple resonances to design flybys that transition between these resonances in the circular restricted three-body problem without the need for two-body approximations. [View Full Paper]

AAS 11 – 126

Fuel-Optimal Trajectories for Continuous-Thrust Orbital Rendezvous With Collision Avoidance Constraint

Richard Epenoy, Centre National d'Etudes Spatiales, Toulouse, France

This paper focuses on the design of a fuel-optimal maneuver strategy for the rendezvous between an active chaser satellite with continuous-thrust capability and a passive target satellite. The problem is formalized as an optimal control problem subject to a collision avoidance constraint on the path of the chaser satellite. Then, a new method for dealing with this state constraint is built by adapting to the optimal control framework a recently developed approach for solving inequality-constrained nonlinear programming problems. The resulting method implies solving a sequence of unconstrained optimal control problems whose solutions converge toward the solution of the original problem. Convergence of the method is proved and its efficiency is demonstrated through numerical results obtained in the case of a rendezvous in Highly Elliptical Orbit. [View Full Paper]

AAS 11 – 127

Mesh Refinement Strategies for Spacecraft Trajectory Optimization Using Discrete Mechanics and Optimal Control

Ashley Moore and **Jerrold E. Marsden**, Control and Dynamical Systems, California Institute of Technology, Pasadena, California, U.S.A.; **Sina Ober-Blöbaum**, Computational Dynamics and Optimal Control, University of Paderborn, Germany

Optimization of spacecraft trajectories using Discrete Mechanics and Optimal Control (DMOC) requires deliberate design of the time grid, or discretization mesh, because the highly nonlinear dynamics require finer time stepping near planets or moons while coarser step sizes are sufficient elsewhere. The mesh refinement schemes presented here provide an automated approach to the step size design. Conventional mesh refinement focuses on improving errors in the solution. Since DMOC is based on a structure-preserving discretization that accurately reflects the qualitative behavior of the solution, such as the energy evolution, this work also explores mesh refinement strategies that aim to minimize the energy error. Additionally, time adaption based entirely on the dynamics is examined. These mesh refinement schemes are first tested on an elliptical orbit transfer modeled by the two body problem and then on the Shoot the Moon problem, an energy efficient transfer from the Earth to the Moon. While energy error and solution error based mesh refinement both demonstrate improvement, time adaption according to the dynamics shows the most promise. [View Full Paper]

AAS 11 – 128

Modified Chebyshev-Picard Iteration Methods for Solution of Boundary Value Problems

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

Modified Chebyshev-Picard iteration methods are presented for solving boundary value problems. Chebyshev polynomials are used to approximate the state trajectory in Picard iterations, while the boundary conditions are maintained by constraining the coefficients of the Chebyshev polynomials. Using Picard iteration and Clenshaw–Curtis quadrature, the presented methods iteratively refine an orthogonal function approximation of the entire state trajectory, in contrast to step-wise, forward integration approaches, which render the methods well-suited for parallel computation since computation of force functions along each path iteration can be rigorously distributed over many parallel cores with negligible cross communication needed. The presented methods solve optimal control problems through Pontryagin's principle without requiring shooting methods or gradient information. The methods are demonstrated to be computationally efficient and strikingly accurate when compared with Battin's method for a classical Lambert's problem and with a Chebyshev pseudospectral method for an optimal trajectory design problem. The reported simulation results obtained on a serial machine suggest a strong basis for optimism of using the presented methods for solving more challenging boundary value problems, especially when highly parallel architectures are fully exploited. [View Full Paper]

AAS 11 – 129

Multiobjective Optimization of Low-Energy Trajectories Using Optimal Control on Dynamical Channels (Part I)

Thomas M. Coffee, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.; **Rodney L. Anderson** and **Martin W. Lo**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

We introduce an automated approach to design efficient low-energy trajectories by extracting initial solutions from dynamical channels formed by invariant manifolds, and improving these solutions through variational optimal control. We consider trajectories connecting two unstable periodic orbits in the circular restricted 3-body problem (CR3BP). Using the example of an Earth-Moon libration orbit transfer, this paper demonstrates an algorithm for extracting a range of efficient solutions from dynamical channels using adaptive numerical methods, and describes how the algorithm may be extended using primer vector theory to iteratively improve these solutions into an approximation of the multiobjective Pareto front. [View Full Paper]

AAS 11 – 130

(Paper Withdrawn)

AAS 11 – 131

Trajectory Design Using Periapse Poincaré Maps and Invariant Manifolds

A. F. Haapala and **K. C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana

Previous researchers have demonstrated that the periapse Poincaré map is very useful to deliver insight into trajectory behavior near the smaller primary within the context of the restricted three-body problem. In this investigation, periapse maps are employed as a design tool for the construction of both planar and three-dimensional transit trajectories with predetermined characteristics. The design strategies are demonstrated via examples that include transit trajectories, as well as heteroclinic connections. Besides mission design, these techniques are also applied to generate path approximations for several Jupiter family comets. [View Full Paper]

SESSION 5: ATTITUDE DETERMINATION
Chair: Dr. Don Mackison, University of Colorado

AAS 11 – 132

Attitude Estimation for Picosatellites With Distributed Computing Platform Using Murrell's Algorithm of the Extended Kalman Filter

Sharan Asundi and **Norman Fitz-Coy**, Mechanical and Aerospace Engineering Department, University of Florida, Gainesville, Florida, U.S.A.; **Haniph Latchman**, Electrical and Computer Engineering, University of Florida, Gainesville, Florida, U.S.A.

Picosatellites have limited capabilities for hosting precise attitude and inertial sensors and the available computational resources are at premium. SwampSat is one such picosatellite under development at the University of Florida with the objective of demonstrating precision three axes attitude control. The satellite hosts a distributed computing system comprised of a low power flight computer and a high speed digital signal processor (DSP). The flight computer, designed to execute routine operations, is interfaced with coarse attitude sensors. The DSP, operated intermittently, interfaces with an inertial measurement unit and hosts Murrell's version of the extended Kalman filter, designed for computationally limited satellites. The work presented describes the attitude estimation algorithm adapted for the distributed computing platform of SwampSat and the mission design for enabling it on orbit during attitude determination and control maneuvers. Results of the simulations carried out to evaluate the need for an estimation algorithm for SwampSat and its effectiveness are discussed. [View Full Paper]

AAS 11 – 133

Attitude Estimation Using Multiplicative Measurement Model

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

A corrected measurement model is presented for observed line-of-sight vectors while dealing with the Wahba problem. The corrected model is derived from the multiplicative measurement model and the error should obey to zero mean white noises. It is proved on both principle axis and rotated angle that the correction would lead to a statically better solution. The essence of correction is to pull estimate by original measurements closer to the true value by enlarge all errors. Theoretically, such correction can be adapted to any kind of least squares. With more measurements, the accuracy gains will be larger, for the statistic effect is more evident. [View Full Paper]

AAS 11 – 134

Attitude Parameterizations as Higher Dimensional Map Projections

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

A generalization is proposed for a class of three-parameter attitude representations that are formulated as a product of the unit rotation vector and various functions of the rotation angle. When related to a four-dimensional unit quaternion, these three-dimensional representations are shown to be analogous to higher-dimensional azimuthal map projections from a three-dimensional unit sphere. Several types of these parameterizations are examined. Their relationships to the rotation matrix and their kinematics are derived. It is shown that kinematical passivity and optimality of the Rodrigues and modified Rodrigues parameters is a special case of the more general result that holds for a wider range of attitude representations. This result is used to formulate and compare passivity based control laws using various attitude representations.
[View Full Paper]

AAS 11 – 135

Enhancements to the *K*-Vector Search Technique

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

The *k*-vector range search technique has been applied to single and multidimensional databases. The *k*-vector has seen extensive success in the star tracking literature as an optimal time range search technique for determining candidate matches for star identification. Unfortunately, nonlinearities in the databases slow down this range searching technique. To avoid this problem, two enhancements to this technique which increase the average performance of the *k*-vector technique for nonlinear and dynamic databases, are presented. The analytical gain in performance with respect to database nonlinearities is discussed along with an information theoretic approach to database partitioning which allows the enhanced *k*-Vector to apply locally resulting in effective piecewise linear *k*-vectors. [View Full Paper]

AAS 11 – 136

Integrated Power Reduction and Adaptive Attitude Control System of a VSCMG-Based Satellite

D. Kim, **N. Fitz-Coy** and **W. E. Dixon**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.; **F. A. Leve**, Air Force Research Lab, Albuquerque, New Mexico, U.S.A.

An adaptive attitude controller developed for satellite that is actuated by a pyramidal arrangement of four single gimbal VSCMGs. To develop the controller from a cascade connection of satellite, gimbal, and wheel dynamics equations, a back-stepping method is exploited. Internal friction is included in the torque expressions of the gimbal and the wheel assemblies. When scaling the size of the VSCMGs, friction effects are significant. A null motion strategy is developed to simultaneously perform the gimbal reconfiguration for singularity avoidance and wheel speed regularization for momentum management. The applied torques of both the gimbals and the wheels containing friction losses contribute to power reduction when in deceleration mode and momentum management resulting from the null motion enables reduced power consumption.
[View Full Paper]

AAS 11 – 137

Optimal Fusion of Vector Observations With Angle or GPS Phase Difference Observations for Three-Axis Attitude Determination

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

The general problem of determining the three-axis attitude from a combination of vector and angle or GPS phase difference observations is examined. Two cost functions, one for vector observations and one for angle or GPS phase difference observations, are combined into a single maximum likelihood cost function. The initial attitude estimate is found and then updated using the Newton estimation sequence until it converges to the optimal estimate. The numerical examples are presented that demonstrate effectiveness of the new approach. [View Full Paper]

AAS 11 – 138

Relative Attitude Determination Using Multiple Constraints

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

In this paper a relative attitude determination solution of a formation of two vehicles with multiple constraints is shown. The solution for the relative attitude between the two vehicles is obtained only using line-of-sight measurements between them and common (unknown) objects observed by both vehicles. The constraints used in the solution are formed from triangles on the vector observations. Multiple constraints are used for each object and the solution is cast into a Wahba problem formulation. Simulation runs are shown that study the performance of the new approach. [View Full Paper]

SESSION 6: RENDEZVOUS AND PROXIMITY MISSIONS
Chair: Dr. Thomas Lovell, Air Force Research Laboratory

AAS 11 – 139

Spacecraft Proximity Operations Using Continuous Low Thrust

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

Recently, both DoD and NASA have demonstrated increased interest in the development of close proximity operations for space systems. AFRL's Advanced Sciences and Technology Research Institute for Astrodynamics (ASTRIA) has defined several key research topics relevant to military priorities, with one area of critical importance being the inspection and observation of low Earth orbit resident space objects (RSOs). This study investigates the feasibility of using an ion propulsion system to effectively and accurately facilitate resident space object inspection. This would allow for a spacecraft to utilize a single thruster for orbital maneuvering and proximity operations. More specifically, this research aims to determine the inefficiencies and challenges associated with using a fixed-thrust engine for autonomous RSO inspection and then proceeds to find resolutions for such challenges. A range of feasible circumnavigation distances that may be accomplished for a given fixed ion propulsion system thrust level is also sought to determine promising mission scenarios. These scenarios are then found for a series of different thrust levels and assessed to produce a topographical graph with the ion thrust level and the circumnavigation distance. This preliminary study shows promise for further investigation into the use of ion propulsion for proximity operations, including a novel path and controller design. Results are presented to demonstrate the feasibility of ion propulsion systems for use in spacecraft proximity operations in low Earth orbits.
[View Full Paper]

AAS 11 – 140
(Paper Withdrawn)

AAS 11 – 141
(Paper Withdrawn)

AAS 11 – 142

Linear Quadratic Model Predictive Control Approach to Spacecraft Rendezvous and Docking

Hyeongjun Park and **Ilya Kolmanovsky**, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.; **Stefano Di Cairano**, Powertrain Control R&A, Ford Motor Company, Dearborn, Michigan, U.S.A.

We consider an application of computationally feasible linear quadratic Model Predictive Control (MPC) framework to spacecraft rendezvous and proximity maneuvers. In this approach, a spacecraft model is used for repeated prediction and optimization of spacecraft motion while dynamically reconfigurable constraints are enforced to maintain the spacecraft position within the Line-of-Sight (LOS) cone from the docking port on the target platform which may be rotating. In addition, the constraints on thrust magnitude and on approach velocity must be fulfilled. The constraints on approach velocity guarantee that the spacecraft velocity matches the velocity of the docking port. For the case of non-rotating platform, an explicit off-line solution of the MPC optimization problem is performed to obtain a piecewise affine control law suitable for on-line implementation without an onboard optimizer. Simulation results demonstrate the ability of the MPC controller to successfully perform the specified maneuvers and compensate for the effects of the unmeasured disturbances. In the case of rotating platform, the prediction of changes in the LOS cone constraints as the platform rotates ensures maneuver completion for higher platform rotational velocities, and it also lowers the fuel consumption. Finally, a relation is exemplified between the control penalty parameter in the quadratic MPC cost function and spacecraft fuel consumption and time-to-dock.
[View Full Paper]

AAS 11 – 143

Position Estimation Using Multiplicative Measurement Model

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

Three novel correction measurement models are presented for vision-based proximity navigation by multiplicative measurement model. They are derived from the statistic characteristics of the measurements. The full correction model is to move original measurement farther away from estimate within the plane defined by measurement and estimate. Such movement decreases the component of noise on the plane of estimate and true direction. Multiple correction and single correction are directly utilizing the form and expectation of multiplicative measurement model. Numerical tests demonstrate that the first model is very significant, the second one is effective under certain circumstances, and the last one usually can be ignored. [View Full Paper]

AAS 11 – 144

Procedure for Determining Spacecraft Collision Probability During Orbital Rendezvous and Proximity Operations

Michael R. Phillips and **David K. Geller**, Department of Mechanical and Aerospace Engineering, Utah State University, Logan, Utah, U.S.A.; **Frank Chavez**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

This paper discusses the development of an algorithm intended to estimate satellite collision probability during orbital rendezvous and proximity operations. It is assumed that the satellite dynamics are described by the Clohessy-Wiltshire equations. The algorithm utilizes a series of metrics that can be placed into three main categories. The first category provides an estimate of the instantaneous probability of collision. It also places an upper bound on the total probability of collision. The second category of metrics provide an estimate of total collision probability, and the last category is Monte Carlo analysis. The metrics are arranged in a hierarchy such that those metrics which can be computed quickest are calculated first. As the algorithm progresses the metrics generally become more costly to compute, but yield more accurate estimates of collision probability. Each metric is compared to a threshold value. If it exceeds the limits determined by mission constraints the algorithm seeks a more accurate estimate by calculating the next metric in the series. If the limit is not reached it is assumed there is a tolerable collision risk, and the algorithm is terminated. In this way the algorithm is capable of adapting so that it is sufficiently accurate without needless calculations being performed. This approach provides a conceptual framework in which collision probability can be systematically estimated. [View Full Paper]

AAS 11 – 145

Relative GPS Navigation for H-II Transfer Vehicle: Design and On-Orbit Results

Shoji Yoshikawa and **Masaharu Suzuki**, Mitsubishi Electric Corporation, Japan; **Jun Tsukui** and **Hifumi Yamamoto**, Mitsubishi Space Software Corporation, Japan; **Toru Kasai**, Japan Aerospace Exploration Agency (JAXA), Japan

Relative GPS navigation (RGPS) filter estimates relative position and velocity of H-II Transfer Vehicle (HTV) based on GPS signals received by GPS receivers on HTV and International Space Station (ISS). It starts about several hundreds of thousand meters from ISS when proximity communication between HTV and ISS is established and hands over to the next navigation sensor (rendezvous sensor) at five hundred meters below the ISS. We will describe the design philosophy of the RGPS filter and report its performance results during the verification flight of HTV in September of 2009.
[View Full Paper]

AAS 11 – 146

Trajectory Design Considerations for Small-Body Touch-and-Go

Mark S. Wallace, **Stephen Broschart**, **Eugene Bonfiglio**, **Shyam Bhaskharan** and **Alberto Cangahuala**, Autonomous Systems Division, Jet Propulsion Laboratory/ California Institute of Technology, Pasadena, California, U.S.A.

"Touch-and-Go," or TAG, is an approach to small-body surface interrogation missions in which the spacecraft descends to the surface, remains in contact for a short time, and then ascends without coming to rest. Appropriate trajectory design solutions to support TAG missions vary widely based on the spacecraft dynamics, small-body environment, spacecraft and ground systems capabilities, and mission objectives. This paper discusses various factors that are considered during the process of developing a TAG mission trajectory and presents a few case study examples to demonstrate how TAG trajectories may vary from mission to mission. [View Full Paper]

SESSION 7: SPACE SURVEILLANCE
Chair: John Seago, Analytical Graphics, Inc.

AAS 11 – 147

Analytic Orbit Design for Earth Sites Observation

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

Satellite observations of specific Earth sites/regions usually require the use of compatible (resonant) orbits. If the observing sensor is optimized for a given altitude then the orbit must also be circular. This work provides an analytical study of the satellite ground track of any compatible and circular orbits for a full repetition cycle. The purpose is to provide analytical derivation of all the points in which the ground track crosses itself, here called X-points. The geographical locations of these points and the approximate expressions of the associated dwell times allow to develop optimal orbit design to best serve the mission. [View Full Paper]

AAS 11 – 148

Information Theoretic Space Object Data Association Methods Using an Adaptive Gaussian Sum Filter

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

This paper shows an approach to improve the statistical validity of orbital estimates and uncertainties as well as a method of associating measurements with the correct space objects. The approach involves using an adaptive Gaussian mixture solution to the Fokker-Planck-Kolmogorov equation for its applicability to the space object tracking problem. The Fokker-Planck-Kolmogorov equation describes the time-evolution of the probability density function for nonlinear stochastic systems with Gaussian inputs, which often results in non-Gaussian outputs. The adaptive Gaussian sum filter provides a computationally efficient and accurate solution for this equation, which captures the non-Gaussian behavior associated with these nonlinear stochastic systems. This adaptive filter is designed to be scalable, relatively efficient for solutions of this type, and thus is able to handle the nonlinear effects which are common in the estimation of resident space object orbital states. The main purpose of this paper is to develop a technique for data association based on information theoretic approaches that are compatible with the adaptive Gaussian sum filter. The adaptive filter and corresponding measurement association methods are evaluated using simulated data in realistic scenarios to determine their performance and feasibility. [View Full Paper]

AAS 11 – 149

Inverse Problems in Unresolved Space Object Identification

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

This paper addresses issues in Space Situational Awareness (SSA), more specifically in the area of low observables. The specific questions addressed relate to handling model uncertainties in the solution of inverse problems associated with non-resolved space objects and representing confidence in the conclusions and decisions based on the solution. In this paper, we pose an inverse problem for a system of nonlinear differential equations. Additionally, we study inverse problems in identification of the orientation states and the shape and size of the space objects. Objects in low earth orbits are modeled using the two body orbit equations including drag perturbations. The drag term is modeled accurately to account for the changing projected area due to the tumbling object. The attitude of the object is represented using the Modified Rodrigues Parameters. The moment of inertia and the mass of the object is computed at each step in the inverse problem from the estimates of the object dimensions. The measurements are assumed to be azimuth, elevation, and the intensity of light (light curve data). It is however assumed that the object is a cuboid characterized by length, width and height. An Unscented Kalman Filter framework is setup for simultaneous position, velocity, attitude, angular velocity and object shape estimation. Monte Carlo simulations are performed to verify the results. [View Full Paper]

AAS 11 – 150
(Paper Withdrawn)

AAS 11 – 151

Ephemeris Requirements for Space Situational Awareness

Daniel L. Oltrogge and **T. S. Kelso**, AGI's Center for Space Standards and Innovation, Colorado Springs, Colorado, U.S.A.; **John H. Seago**, Analytical Graphics Inc., Exton, Pennsylvania, U.S.A.

Increasing international cooperation in the areas of orbital collision avoidance and electro-magnetic interference mitigation has driven the exchange of satellite ephemerides to support Space Situational Awareness, threat detection, and avoidance. To be useful, ephemerides must conform to certain specifications in order to ensure that the intended precision of these analyses is achieved. This paper examines the accuracy of various interpolation methods as a function of ephemeris step size and ephemeris numerical precision for a variety of orbital regimes. [View Full Paper]

AAS 11 – 152

Sliding Window Batch Estimation Filtering for Enhanced Anomaly Detection and Uncorrelated Track Resolution

Joshua T. Horwood, **Nathan D. Aragon** and **Aubrey B. Poore**,
Numerica Corporation, Loveland, Colorado, U.S.A.

A sliding window batch estimation filter (SWBEF) is proposed which bypasses the expensive representation of highly non-Gaussian densities arising from the prediction step of the Bayesian state estimator. Instead, the SWBEF waits until a new report (measurement, track) becomes available and then performs the prediction and correction steps simultaneously. This filter is well suited for anomaly detection and UCT resolution. Through a LEO simulation scenario motivated from real orbital data, it is demonstrated that the algorithm provides accuracy comparable to a high fidelity Gaussian sum filter yet has computational cost commensurate with a standard unscented Kalman filter. [View Full Paper]

AAS 11 – 153

Spectral Decomposition of Orbital Tori

Ralph E. Bordner III, Major, USAF, Layered Sensing Exploitation Division, Sensors Directorate, Air Force Research Laboratory, Wright-Patterson AFB, Ohio, U.S.A.; **William E. Wiesel**, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, U.S.A.

The assertion that earth orbiting satellites under the influence of the geopotential are Kolmogorov-Arnold-Moser (KAM) tori is the underlying premise of this work. Trajectory following spectral methods were applied to decompose orbits into multi-periodic Fourier series, effectively compressing ephemerides for long-term use. The proposed approach focused on fitting local spectral structures, denoted as frequency clusters, within the orbital data as opposed to fitting every Fourier series coefficient simultaneously, which is significantly more numerically efficient. With integrated data, maximum error in the fits were as low as a few meters per coordinate axis over a 1 year period. [View Full Paper]

AAS 11 – 154

Covariance Error Assessment, Correction, and Impact on Probability of Collision

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

The probability of collision, the principal metric in collision risk assessment, is reliant on an accurate representation of the covariance of the state vectors at the time of closest approach. This document provides a theoretical description for how one can estimate errors in covariances and correct for them. In addition, a method is developed to calculate both the errors in these computations and the effect of these uncertainties on the probability of collision as a whole. [View Full Paper]

SESSION 8: TRAJECTORY DESIGN AND OPTIMIZATION II
Chair: Dr. Chris Ranieri, The Aerospace Corporation

AAS 11 – 155

A Direct Method for Trajectory Optimization Using the Particle Swarm Approach

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

The particle swarm optimization (PSO) technique is utilized to solve a variety of trajectory optimization problems. PSO is a stochastic global optimization method which relies on a group of potential solutions to explore the search space. Conceptually, each particle in the swarm utilizes its own memory as well as the knowledge accumulated by the entire swarm to iteratively converge on the optimal solution. It is relatively easy to implement, and unlike gradient-based solvers, does not require an initial guess or continuity in the problem definition. Although PSO has been successfully employed in solving discrete optimization problems, its application in dynamic optimization, as posed in the Optimal Control Theory, has been little explored. In this work, we use PSO to generate near-optimal solutions to several non-trivial trajectory optimization problems, including thrust programming for minimum-fuel, multi-burn coplanar rendezvous, and computing the maximum altitude climb path for an aircraft. The control functions are assumed to be linear combination of B-Splines, the coefficients of which are selected by the swarm optimizer. A dynamic multi-stage-assignment penalty function is incorporated to enforce the associated constraints. Finally, for each of the test cases considered, the PSO solution is compared with its gradient-based counterpart. [View Full Paper]

AAS 11 – 156

A New Numerical Optimization Method Based on Taylor Series

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

A new method to numerically solve trajectory optimization problems is developed. The method uses direct transcription to convert the continuous optimal control problem into a parameter optimization problem that can be solved with non-linear programming. A high-order Taylor series expansion about each node is used to convert the system equations into algebraic constraint equations. Automatic differentiation is used to compute the derivatives of the system equations required to keep arbitrarily many terms in the Taylor series. Several orbit transfer problems are solved to evaluate the performance of the new method. [View Full Paper]

AAS 10 – 157
(Paper Withdrawn)

AAS 11 – 158

Global Point Mascon Models for Simple, Accurate and Parallel Geopotential Computation

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

High-fidelity geopotential calculation using spherical harmonics (SH) is expensive and relies on recursive non-parallel relations. Here, a global point mascon (PMC) model is proposed that is memory light, extremely simple to implement (at any derivative level), and is naturally amenable to parallelism. The gravity inversion problem is posed classically as a large and dense least squares estimation problem. The well known ill-conditioned nature of the inversion is overcome in part using orthogonal solution methods, a judicious choice for the mascon distribution, and numerically preferred summation techniques. A variety of resolutions are examined including PMC models with up to 30,720 mascons. Measurements are simulated using truncated SH evaluations from the GGM02C gravity field derived from the GRACE spacecraft. Resolutions are chosen in order to target residual levels at least an order of magnitude smaller than the published expected errors of the GGM02C. A single Central Processing Unit (CPU) implementation is found to be approximately equal in speed compared to SH for all resolutions while a parallel implementation on an inexpensive Graphics Processing Unit (GPU) leads to order of magnitude (13 to 16 times) speedups in the case of a 156×156 gravity field. A single CPU Matlab implementation is competitive in speed with compiled code due to Matlab's efficient use of large matrix operations. [View Full Paper]

AAS 11 – 159

Optimal Autonomous Mission Planning Via Evolutionary Algorithms

Jacob A. Englander and **Bruce A. Conway**, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.;
Trevor Williams, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Many space mission planning problems may be formulated as hybrid optimal control problems, i.e. problems that include both real-valued variables and categorical variables. In orbital mechanics problems the categorical variables will typically specify the sequence of events that qualitatively describe the trajectory or mission, and the real-valued variables will represent the launch date, flight times between planets, magnitudes and directions of rocket burns, flyby altitudes, etc. A current practice is to pre-prune the categorical state space to limit the number of possible missions to a number whose cost may reasonably be evaluated. Of course this risks pruning away the optimal solution. The method to be developed here avoids the need for pre-pruning by incorporating a new solution approach. The new approach uses nested loops; an outer-loop problem solver that handles the finite dynamics and finds a solution sequence in terms of the categorical variables, and an inner-loop problem solver that finds the optimal trajectory for a given sequence A binary genetic algorithm is used to solve the outer-loop problem, and a cooperative algorithm based on particle swarm optimization and differential evolution is used to solve the inner-loop problem. The HOCP solver is successfully demonstrated here by reproducing the Galileo and Cassini missions. [View Full Paper]

AAS 11 – 160

Finding Optimal Relative Orbit Transfer Trajectories With the Particle Swarm Algorithm and Primer Vector Theory

Brianna Aubin, **Bruce Conway** and **Soon-Jo Chung**, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, U.S.A.

Spacecraft formation flights are a useful tool to improve mission cost-effectiveness and redundancy, but controlling the satellites within the cluster is a difficult task. The particle swarm evolutionary algorithm is used to find ways to minimize the amount of fuel required for impulsive transfers between periodic orbits in the relative motion problem. Relative orbit elements are used in order to create the solution vectors for the particle swarm, and the Clohessy-Wiltshire-Hill equations are used to define the relative motion of the satellites. These trajectories are then analyzed according to primer vector theory, in order to check the optimality of the trajectories developed via the particle swarm algorithm and determine if they may be improved. [View Full Paper]

AAS 11 – 161

Parallel Evaluation of Poisson Series

Juan F. San-Juan, **David Ortigosa** and **Montserrat San-Martín**, Universidad de La Rioja, ES-26004 Logroño, Spain

In the present paper, using Open Multi-Processing (OpenMP) paradigm, we increase the efficiency of the evaluation program of Poisson series generated by MathATESAT by parallelizing the core of this algorithm. These are the mathematical objects which appear in the process of evaluation of an analytical theory with the purpose of calculating the position and velocity of a body at any given time or for locating frozen orbits. Finally, in order to illustrate this parallelized algorithm, we consider two examples; the first, related to an AOPP derived from a 6 x 6 tesseral model, only valid for the non-resonance case, and in the second we revise the MZ6PPKB2 and MZ6PPKB3 AOPPs, derived from a zonal analytical theory for Mars orbiters.
[View Full Paper]

AAS 11 – 162

Particle Swarm Optimization of Low-Thrust Orbital Transfers and Rendezvous

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

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

SESSION 9: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL

Chair: Dr. David Spencer, Pennsylvania State University

AAS 10 – 163

(Paper Withdrawn)

AAS 11 – 164

In-Orbit Estimation of Inertia and Momentum-Actuator Alignment Parameters

Michael C. Norman and **Mason A. Peck**, Department of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York, U.S.A.; **Daniel J. O'Shaughnessy**, The Johns Hopkins Applied Physics Laboratory, Laurel, Maryland, U.S.A.

Knowledge of the mass distribution and momentum actuator alignment parameters of a spacecraft is vital to the control of its attitude motion. The difficulty of measuring the complete set of these quantities prior to launch along with the potential for changes in the spacecraft mass distribution during operations suggests the utility of estimating these parameters in-orbit from available telemetry data. This paper develops a series of possible on-board parameter estimation schemes based on measurement equations describing the angular momentum and kinetic energy states of the rigid-body system. The performance of the algorithms is compared over both a simulated maneuver and a series of data sets from the MESSENGER spacecraft. [View Full Paper]

AAS 11 – 165
(Paper Withdrawn)

AAS 11 – 166
Near-Optimal Feedback Guidance for an Accurate Lunar Landing

Joseph Parsley and **Rajnish Sharma**, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, Alabama, U.S.A.

This paper presents a new guidance method for a lunar landing problem. The method allows a craft to land accurately, efficiently, and autonomously. To facilitate the success of this method, it is proposed that the Moon will be provisioned with prepared landing zones and very accurate navigational aids. To estimate the precise order of control for an optimal trajectory, the lunar landing problem, which is nonlinear, is formulated as a finite-time, fixed-terminal optimal control problem (OCP). To solve the OCP in a feedback form, a new extension of State-Dependent Riccati Equation (SDRE) technique is investigated for terminally constrained problems, and then it is applied to the formulated OCP. The solution obtained using the extended SDRE technique is further investigated for accuracy, robustness, and computational efficiency. Also, to ascertain the accuracy of the numerical results, the final feedback solution is compared with the open-loop optimal solution. [View Full Paper]

AAS 11 – 167
Non-Linear Sliding Guidance Algorithms for Precision Lunar Landing

Roberto Furfaro, Department of Systems and Industrial Engineering, University of Arizona, Tucson Arizona, U.S.A.; **Scott Selnick**, **Michael L. Cupples** and **Matthew W. Cribb**, Raytheon Missile Systems, Tucson Arizona, U.S.A.

Two classes of non-linear guidance algorithms for lunar precision landing are presented. The development of such algorithms is motivated by the need of more stringent landing requirements imposed by future lunar mission architectures (e.g. the ability to land anywhere from a generic lunar orbit). The first class of guidance algorithms, called Optimal Sliding Guidance (OSG) laws, analytically determine the optimal acceleration command and augment it with a sliding mode to provide robustness against perturbations. The second class of guidance algorithms, called Multiple Sliding Surface Guidance (MSSG) laws, employs two interconnected sliding surfaces to track an on-board generated trajectory that drive the descending lander to the desired location at the desired velocity. For both guidance algorithms, which are proven to be globally stable, a set of Monte Carlo simulations have been executed to verify their performances. Both algorithms perform very well, i.e. they exhibit precision a with very low guidance residual errors on the desired target point above the lunar surface. Overall, MSSG shows slightly better performances with two drawbacks: 1) it needs more propellant mass and 2) it requires a higher frequency guidance loop (greater or equal than 100 Hz). The latter it imposes more challenging requirements on the design of the lander avionics system. Conversely, OSG tends to behave in a smoother fashion with excellent landing performance, lower guidance cycle frequency (10 Hz) and less propellant mass. Importantly, MSSG may be employed as real-time guidance scheme to track trajectory generated by more conventional, Apollo-like targeting algorithms. [View Full Paper]

AAS 11 – 168

Nonlinear Tracking Control of Maneuvering Rigid Spacecraft

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

Nonlinear optimal control formulations have been considered where the state equation consists of the nonlinear state variables. These approaches seek to drive the terminal state values to zero, but require an n-th order polynomial expansion in all of the state variables, leading to tensor-based math models. As with any tensor-based models one is not assured that the control solution converges after retaining a finite number of terms. This problem is overcome by reformulating the control problem in terms of an error state relative to a reference trajectory; thereby yielding a more rapidly converging tensor series approximation for the control. The full nonlinear error dynamics for kinematics and the equation of motion is retained, yielding a tensor-based series solution for the Co-State as a function of error dynamics. A generalized Riccati matrix and disturbance rejection control formulation is presented that accounts for the state nonlinearity through second order. Modified Rodrigues Parameters (MRPs) are used for describing the tracking orientation error dynamics. Computational differentiation is used to define an array-of-arrays data structure for computing 1st, 2nd and 3rd order tensor models for the error dynamics. Spacecraft tracking control applications are presented. The proposed nonlinearly coupled Riccati disturbance rejection gain modeling approach is expected to be broadly useful for applications science and engineering. [View Full Paper]

AAS 11 – 169

Optimal Guidance for Quasi-Planar Lunar Descent with Throttling

David G. Hull, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.

The thrust pitch and yaw controls for the minimum-time rocket transfer over a flat moon with constant thrust are used to study guidance for the lunar descent problem. In order to obtain a geometrically-simple solution, the free-downrange optimal controls are used, and the thrust magnitude is changed to satisfy the downrange constraint. After assuming that the descent is nearly planar (small yaw), three approximate pitch solutions are investigated, exact pitch, first-order pitch, and zeroth-order pitch, to determine the level of approximation that can be tolerated for descent. Preliminary guidance results are presented. [View Full Paper]

AAS 11 – 170

The Effects of Time Delay on Precision Attitude Control of Plug-and-Play Satellites

Kunal Patankar and **Norman Fitz-Coy**, Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, Florida, U.S.A.;
C. Douglas McFarland, Guidance, Navigation & Control Group, Air Force Research Laboratory Space Vehicle Directorate, Kirtland AFB, New Mexico, U.S.A.

This paper characterizes the effects of time delays on the precision attitude control of small satellites in order to bound the mission performance of satellites using the Space Plug-and-Play Avionics (SPA) data bus standard. This is accomplished through a systematic examination of the performance degradation for generalized spacecraft pointing maneuvers. Propagation delays are introduced in sensor measurements and actuation commands to simulate the communication delays caused by the SPA data bus. Nonlinear and linear system models are developed, analyzed, simulated and compared in order to assess viability of quantifying the performance changes of the ADCS for a SPA-based spacecraft. [View Full Paper]

SESSION 10: ORBITAL DEBRIS AND SPACE ENVIRONMENT
Chair: Dr. Thomas Eller, Astro USA, LLC

AAS 11 – 171

Dynamics of Debris Cloud Motion Based on Relative Orbit Elements

Jianfeng Yin, **Ye Liang**, **Qinqin Luo** and **Chao Han**,
Beihang University, Beijing, China

This paper derives a precise analytical geometric model for debris cloud, including the effects of the reference orbit eccentricity and the primary gravitational perturbation $J2$. Relative orbit elements (ROE) are defined as a set of parameters that describe the debris cloud motion, based on the concept of control for geostationary satellite. The linear equations for relative motion are deduced based on ROE and the curvilinear coordinate system. The error analysis and simulations presented clearly show that the geometric model could describe debris cloud evolution more efficiently, while the velocity increment is not very large. [View Full Paper]

AAS 11 – 172

Examination of SGP4 Accuracy in Orbit Prediction using the Champ Satellite

Shaokai Wang and **Chao Han**,
School of Astronautics, Beihang University, Beijing, China

The accuracy of SGP4 implemented in space debris orbit prediction is important factor for collision avoidance issues. This paper examines the accuracy using quick orbit data from CHAMP satellite. A large database of accurate orbit data from CHAMP satellite was available to serve as the truth reference in this study. Then according to the "truth orbit", the accuracy of SGP4 is analyzed. The error is displayed in the radial direction, in-track direction, and cross-track direction (RIC) for better use in collision avoidance, especially in the method of conjunction box. [View Full Paper]

AAS 11 – 173

Extension of a Simple Mathematical Model for Orbital Debris Proliferation and Mitigation

Jarret M. Lafleur, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.

A significant threat to the future of space utilization is the proliferation of debris in low Earth orbit. To facilitate quantification of trends and the assessment of potential mitigation measures, this paper extends a previously proposed analytic debris proliferation model consisting of two coupled differential equations. Analyzed are the transient and equilibrium behavior of the parametric model, leading to assessment of the likely effectiveness of potential debris mitigation measures. Results suggest the current equilibrium capacity for intact satellites in low Earth orbit allows for only 25% of the satellites in orbit today and presents an average 2.8% per year risk of catastrophic collision for individual satellites. Results also suggest that direct removal of debris fragments has the potential to add decades or centuries of useful life to low Earth orbit. In addition to providing numerical results, this paper contributes a simple debris model particularly useful when more sophisticated models are unavailable or prohibitively time-consuming to utilize. [View Full Paper]

AAS 11 – 174

Fitted Drag Coefficients as a Source of Density Information

Craig A. McLaughlin, **Travis F. Lechtenberg**, **Stephen R. Mance**, **Travis Locke** and **Piyush M. Mehta**, Department of Aerospace Engineering, University of Kansas, Lawrence, Kansas, U.S.A.

Drag modeling is the greatest uncertainty in the dynamics of low Earth satellite orbits where ballistic coefficient and density errors dominate drag errors. This paper examines fitted drag coefficients found as part of a precision orbit determination process for Stella and Starlette from 2000 to 2004, GEOSAT Follow-On (GFO) from 2000 to 2002 and 2005, and GFZ-1 from 1995 to 1997. The drag coefficients for the spherical Stella and Starlette satellites are assumed to be highly correlated with density model error and are converted to density model corrections. [View Full Paper]

AAS 11 – 175

Miss Distance – Generalized Variance Non-Central Chi Distribution

Ken Chan, The Aerospace Corporation, Chantilly, Virginia, U.S.A.

In many current practical applications, the probability of collision is often considered as the most meaningful criterion for determining the risk to a spacecraft. However, when the miss distance is very small (say 100 m or less), the collision probability may not comfortably serve well as the only metric for measuring the risk. In these cases, it is also important to know the statistics of the miss distance distribution, particularly the confidence limits that bound the miss distance. One approach to determine the distribution of the miss distance is to perform rather time-consuming Monte Carlo simulations on the two conjuncting objects by choosing random initial conditions at the epoch commensurate with the covariances. The orbit propagations must be of very high precision because accuracies down to the meter range are required. The analysis shown here formulates the problem analytically. For this, we consider the miss distance as given by a non-central chi distribution with unequal variances. This method eliminates the need to perform an inordinate amount of computation. Using this approach, we can reduce the computation time down by several orders of magnitude. [View Full Paper]

AAS 11 – 176

Norad TLE Based Ground Orbit Determination Strategy for Mitigating Space Debris Collisions

Hae-Dong Kim and **Young-Joo Song**, Space Science Department, Space Applications and Future Technology Center, Korea Aerospace Research Institute, Daejeon, Republic of Korea.

Since the Chinese ASAT test in 2007, space debris has become a major concern for government and satellite operators such as the Korea Aerospace Research Institute (KARI) in Korea because we currently operate one multi-purpose low Earth orbit (LEO) satellite, the KOMPSAT-2, and one geostationary satellite, the COMS-1. Indeed, the successors of the KOMPSAT-2, KOMPSAT-3, 3A, and 5 will be launched within the next three years. The mission orbit of those satellites will be located between 500 km and 700 km. That is why the space debris problem has become one of the major issues for the space community in Korea. Accordingly, the mission control center, located at KARI, has analyzed the possibility of a collision between space debris and the KOMPSAT satellite based on the NORAD catalog. However, the prediction accuracy of Two-Line Element (TLE) based orbit is up to several kilometers, according to the prediction time span. In this paper, we propose a NORAD TLE based ground orbit determination strategy to improve the prediction accuracy of TLE based orbit. The main idea is derived from a ground orbit determination strategy using GPS navigation solutions data from an on-board GPS receiver. In order words, the proposed strategy uses NORAD TLEs as pseudo-measurements for the ground orbit determination system based on high precision dynamic models. Earth Centered Earth Fixed position vectors converted from NORAD TLE are processed by a ground orbit determination software based on the Bayesian least squares estimation technique. As a significant preliminary result, the improvement of the prediction accuracy of the proposed strategy has been achieved. [View Full Paper]

AAS 11 – 177

Progress in Standards for Space Operations and Astrodynamics

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

The purpose of this paper is to expose to the astrodynamics community advances in consensus standards for space operations and astrodynamics and to solicit participation in those developments. The paper describes collaboration among several space and astrodynamics standards bodies. Standards recently published and being developed are reviewed. The paper describes technical, political, and diplomatic issues that affect consensus on important normative guidance. Finally, the paper describes the status of two important standards developments: disposal of boosters that remain in orbit and guidance for implementing Universal Coordinated Time. [View Full Paper]

AAS 11 – 178

The Dynamics of High Area-to-Mass Ratio Objects in Earth Orbit: The Effect of Solar Radiation Pressure

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

The effect of solar radiation pressure (SRP) on the orbital evolution of high area-to-mass ratio (HAMR) debris objects in the geosynchronous and Global Positioning System orbits is explored. Objects with area-to-mass ratios ($A{=}M$s) as high as 90 m^2/kg were included in this analysis. We show that for the "cannonball" model of SRP acceleration, the averaged Gauss Equations can be solved in closed form, and predict large variations in eccentricity and inclination over time spans significantly less than a year. The long-term dynamical evolution under this analytical model is compared with results obtained by Anselmo and Pardini (2010), who used a detailed numerical propagator that accounted for the geopotential harmonics, luni-solar perturbations, and direct solar radiation pressure. The amplitudes and periods of the perturbations were found to vary according to the magnitude of the $A{=}M$ values. The general behavior of the evolution was observed to be the same as that reported from the numerical propagator, which shows that many of the extreme dynamical behaviors for these objects are a natural and completely understandable consequence of solar radiation pressure.
[View Full Paper]

SESSION 11: ASTEROID MISSIONS II
Chair: Dr. Matthew Berry, Analytical Graphics, Inc.

AAS 11 – 179

A Strategy for Landings on Small Binary Bodies: Application to Asteroid System 1999 KW4

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

Landing trajectories to the surface of a binary asteroid system are explored. The desire is to deploy a lander from orbit on a ballistic trajectory to the asteroid surface, meaning that active guidance is not needed. We develop a robust deployment scheme that can provide a guaranteed landing on the surface with minimal technological requirements. To perform this we apply concepts from the Circular Restricted 3-Body Problem, suitably modified, that enable such deployments to be designed. We test the robustness of our design by evaluating its performance about realistic asteroid models and with multiple gravitational and non-gravitational perturbations. [View Full Paper]

AAS 11 – 180

Dawn Statistical Maneuver Design for Vesta Operations

Daniel W. Parcher and **Gregory J. Whiffen**, Guidance Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

In July of 2011 the Dawn spacecraft is scheduled to begin orbital operations at Vesta, a large main-belt asteroid. Dawn is a NASA Discovery mission that uses solar-electric low-thrust ion propulsion for both interplanetary cruise and orbital operations. Navigating between the Dawn project's four targeted science orbits at Vesta requires a plan that accounts for uncertainties not only in thrust execution, orbit determination, and other spacecraft forces, but also large uncertainties in characteristics of Vesta – such as the asteroid's gravity field and pole orientation. Accommodating these uncertainties requires strategic use of low-thrust maneuvers reserved for statistical trajectory corrections. This paper describes the placement and evaluation of low-thrust statistical maneuvers during two key phases of the Vesta mission along with a discussion of the tools, constraints, and methods used to plan those maneuvers. [View Full Paper]

AAS 11 – 181

Design of Round-Trip Trajectories to Near-Earth Asteroids Utilizing a Lunar Flyby

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

There are currently over 7,700 known Near-Earth Asteroids (NEAs), and more are being discovered on a continual basis. Current models predict that the actual order of magnitude of the NEA population may range from 105 to 106. The close proximity of NEA orbits to Earth's orbit makes it possible to design short duration round-trip trajectories to NEAs under the proper conditions. In previous work, 59 potentially accessible NEAs were identified for missions that depart Earth between the years 2016 and 2050 and have round-trip flight times of a year or less. We now present a new method for designing round-trip trajectories to NEAs in which the Moon's gravity aids the outbound trajectory via a lunar flyby. In some cases this gravity assist can reduce the overall spacecraft propellant required for the mission, which in turn can allow NEAs to be reached which would otherwise be inaccessible to a given mission architecture. Results are presented for a specific case study on NEA 2003 LN6. [View Full Paper]

AAS 11 – 182

Low Altitude Mapping Orbit Design and Maintenance for the Dawn Discovery Mission at Vesta

Gregory J. Whiffen, Mission Design and Navigation Section, Jet Propulsion Laboratory, Pasadena, California, U.S.A.

NASA's Dawn discovery mission will orbit the giant asteroid Vesta beginning in the summer of 2011. Four different near polar science orbits are planned. The lowest planned orbit at Vesta is called the Low Altitude Mapping Orbit or LAMO and is by far the most challenging to design and maintain due to the strong, nonspherical gravity expected there. This paper describes the orbit selection process. The true gravity field of Vesta remains highly uncertain. The proposed orbit selection process will be applied once sufficient gravity knowledge is obtained at higher orbits. The orbit selection process is applied here to a fictitious gravity field based on a Hubble space telescope shape model for Vesta assuming uniform density. The outcome of the process described here is a variety of stable orbits. However, initially stable orbits at the LAMO altitude are not expected to remain stable operationally due to the unpredictable impulses resulting from the Dawn spacecraft thruster firings to de-saturate its momentum wheels. As a result, orbital maintenance maneuvers will probably be necessary. This paper also briefly describes the statistical maneuver design process that resulted in the orbit maintenance plan. [View Full Paper]

AAS 11 – 183

Low-Thrust Orbit Transfer Design for Dawn Operations at Vesta

Daniel W. Parcher, Guidance Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Upon arrival at the asteroid Vesta, scheduled for July of 2011, the Dawn spacecraft will target a series of four distinct mapping orbits, each providing a unique opportunity to observe Vesta. The unknown, and potentially complex, Vesta gravity field presents challenges for designing low-thrust transfers between these mapping orbits while maintaining spacecraft safety from Vesta occultation of the Sun. This paper provides a description of the orbit transfers designed for Vesta operations along with a discussion of the constraints and methods used to design these transfers. The effect of alternate gravity fields on the viability of the designs and the design method is also considered. [View Full Paper]

AAS 11 – 184

(Paper Withdrawn)

AAS 11 - 185

(Paper Withdrawn)

AAS 11 – 186

The Stability of Powered Flight Around Asteroids With Application to Vesta

Gregory J. Whiffen, Mission Design and Navigation Section, Jet Propulsion Laboratory, Pasadena, California, U.S.A.

The reliability of low-thrust trajectories between science orbits around large asteroids must be evaluated subject to the unavoidable uncertainties of orbit determination, asteroid physical parameters, momentum de-saturation maneuvers, and transfer maneuver execution error. This paper presents a computationally inexpensive way to extend the concept or orbital stability to trajectories undergoing continuously powered low-thrust flight. Trajectories that are stable using this measure are shown to be stable under the combined uncertainties expected during operations. The measure is general and relatively simple to implement. The method was applied to maneuvers planed around the asteroid Vesta in support of NASA's Dawn Discovery mission.
[View Full Paper]

SESSION 12:
DECADAL SURVEY AND INTERPLANETARY MISSION DESIGN
Chair: Jon Sims, Jet Propulsion Laboratory

AAS 11 – 187

Interplanetary Electric Propulsion Chiron Mission Trades Supporting the Decadal Survey

John W. Dankanich, Gray Research, Inc., Cleveland, Ohio, U.S.A.;
Steven R. Oleson, NASA Glenn Research Center, Cleveland, Ohio, U.S.A.

The decadal survey committee was tasked to develop a comprehensive science and mission strategy for planetary science that updates and extends the National Academies Space Studies Board's current solar system exploration decadal survey. A Chiron orbiter mission has been evaluated as a part of this 2015-2025 Planetary Science Decadal Survey. A comprehensive Chiron orbiter mission design was completed, including a broad search of interplanetary transfer options. The scope of interplanetary trades was originally limited to chemical ballistic solutions due to the power constraint of two Advanced Stirling Radioisotope Generators. All ballistic solutions with no more than 13 year transit times were found non-viable. Solar electric propulsion can increase delivered mass, but does not allow for practical insertion velocities. Based on the propulsion limitations, the scope was increased to include radioisotope powered electric propulsion options. Based on those analyses, it is expected that the science mission can be closed with six standard ASRGs with a 13 year transfer or an 11 year transfer using the next generation ASRGs combined with radioisotope electric propulsion. Interplanetary electric propulsion trajectory trades and sensitivity analyses are presented herein.
[View Full Paper]

AAS 11 – 188

Conceptual Mission Design of a Polar Uranus Orbiter and Satellite Tour

James McAdams, **Christopher Scott** and **Yanping Guo**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.; **John Dankanich**, Gray Research, Inc, Cleveland, Ohio, U.S.A.; **Ryan Russell**, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A.

In response to NASA's planetary science decadal survey, this paper outlines the conceptual mission design of a Uranus orbiter. In the baseline design the spacecraft launches during a 21-day launch period in 2020, followed by a 13-year cruise with solar electric propulsion and a single Earth flyby. Repeatable launch opportunities are available from 2021-2023. An atmospheric probe is released 29 days prior to Uranus orbit insertion. After completion of the probe descent phase the spacecraft inserts into a highly inclined elliptical orbit for 431 days, followed by the satellite tour with targeted flybys of five satellites. [View Full Paper]

AAS 11 – 189

Interplanetary Electric Propulsion Uranus Mission Trades Supporting the Decadal Survey

John W. Dankanich, Gray Research, Inc., Cleveland, Ohio, U.S.A.; **James McAdams**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

The Decadal Survey Committee was tasked to develop a comprehensive science and mission strategy for planetary science that updates and extends the National Academies Space Studies Board's current solar system exploration decadal survey. A Uranus orbiter mission has been evaluated as a part of this 2013-2022 Planetary Science Decadal Survey. A comprehensive Uranus orbiter mission design was completed, including a broad search of interplanetary electric propulsion transfer options. The scope of interplanetary trades was limited to electric propulsion concepts, both solar and radioisotope powered. Solar electric propulsion offers significant payloads to Uranus. Inserted mass into the initial science orbit due is highly sensitive to transfer time due to arrival velocities. The recommended baseline trajectory is a 13 year transfer with an Atlas 551, a 1+1 NEXT stage with 15 kW of power using an EEJU trajectory and a 1,000 km EGA flyby altitude constraint. This baseline delivers over 2,000 kg into the initial science orbit. Interplanetary trajectory trades and sensitivity analyses are presented herein.
[View Full Paper]

AAS 11 – 190

Interplanetary Trajectory Design of Space Vehicle With Bimodal Nuclear Propulsion

Oleksandr Dekhtiar and **Oleksii Kharytonov**, Department of Mechanics of Continuous Medium of Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

The investigation of the efficiency of the combination of high- and low-thrust arcs of space vehicle trajectory is carried out for Hohmann-type interplanetary transfer. The high-thrust propulsion is used for planet centric maneuver realization and low-thrust propulsion is used for heliocentric maneuver realization. The efficiency of combination is investigated for the space vehicles with liquid and bi-modal nuclear rocket engines. It is shown that such the efficiency increasing with the increasing of heliocentric maneuver duration and delta velocity. [View Full Paper]

AAS 11 – 191

Jupiter Trojan Orbiter Mission Design Trades Supporting the Decadal Survey

John W. Dankanich, Gray Research, Inc., Cleveland, Ohio, U.S.A.; **James McAdams**, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

NASA's Planetary Science Decadal Survey Committee was tasked to develop a comprehensive science and mission strategy that updates and extends the National Academies Space Studies Board's current solar system exploration decadal survey. A study for a Jupiter Trojan asteroid tour and rendezvous was led by the John's Hopkins University Applied Physics Laboratory. Mission concepts evaluated included ballistic chemical propulsion options and radioisotope electric propulsion options. The trajectory trades for the Jupiter Trojan rendezvous are presented herein. [View Full Paper]

AAS 11 – 192

Trajectory Design of Solar Orbiter Using Earth and Venus Gravity Assists

José M. Sánchez Pérez, Mission Analysis Section, European Space Agency, OPS-GFA, ESOC, Darmstadt, Germany

In the context of the ESA Solar Orbiter mission studies 4 new trajectories are developed , which use unpowered Earth and Venus gravity assist flybys to reach the operational heliocentric orbits with perihelion as close as 0.28 AU (60 solar radii) from which unprecedented Sun observations will be conducted until eventually reaching solar latitudes over 33 deg. This robust trajectory design enabled a "fast-track" mission approach based on the maximum re-use of technologies developed for the ESA Bepi-Colombo mission. This paper presents the design process followed to define the trajectories within the mission requirements and scientific objectives. [View Full Paper]

AAS 11 – 193
(Paper Withdrawn)

SESSION 13: SPECIAL SESSION: INNOVATIVE GNC TEST SOLUTIONS
Chair: Dr. Austin Lee, The Aerospace Corp.

AAS 11 – 194

Attitude Sensors' Miniaturization Facilitates Optimization of Testing Activities

P. Fidanzati, **F. Boldrini** and **E. Monnini**, SELEX Galileo, Campi Bisenzio (FI), Italy; **P. Airey**, ESA ESTEC, AG Noordwijk, The Netherlands

In the frame of an ESA contract, the prototype of a miniaturized Digital Sun Sensor with high accuracy and broad field of view was developed. APS Detector, FPA driver, processing logic, SpaceWire drivers, clock oscillator and power supply sections are embedded on a single chip. Testing and characterization of the prototype gave good results, in line with the design specifications. Thanks to miniaturized dimensions and use of SpaceWire protocol, optimized testing tools and innovative mixed hardware/software testing methods are under study to allow simultaneous testing of several units, leading to a drastic reduction of production time and non recurring costs.
[View Full Paper]

AAS 11 – 195

Control Design for a Six Degree-of-Freedom Shaker

Walter H. Chung, **Allen Raines** and **John Shishido**, The Aerospace Corporation, El Segundo, California, U.S.A.

Modern fiber-optic gyros are vulnerable to low-level, high frequency vibration. To test these gyros for margin, a six degree-of-freedom shaker has been built at The Aerospace Corporation. This shaker was based upon the Stewart-Gough platform, a.k.a. a hexapod. The closed-loop control of this mechanism ran into the limits of the real-time control processor and unexpected changes to the plant dynamics. Classical and modern, i.e. LQG, techniques, were examined but ultimately a mixed-sensitivity H_∞ controller was chosen for the final design. Coupled with a last-minute, ad hoc damper added to the system, this compensator led to a successful design. [View Full Paper]

AAS 11 – 196

Development of a Fine Track System for the Aerospace Laser Communications Testbed

Jason C. Cardema, **Charles M. Klimcak** and **Alinn R. Herrera**,, The Aerospace Corporation, El Segundo, California, U.S.A.

In a laser communications terminal, a received beam can be coupled into a single-mode optical fiber for demodulation by the communications subsystem. Coupling free-space light into an optical fiber requires precise control that can be adversely affected by local jitter disturbances, which can generate excessive optical loss that might disrupt communications. To maximize received power in-fiber, we have designed and built a closed-loop fine tracking system that directs and locks a received laser beam onto the core of a single-mode fiber. This fine tracking system operates by applying a small angular nutation to the received light, generating a pointing error signal that can be extracted by analog demodulation of the power. A fast-steering mirror controller compensates for the measured pointing error. This paper will discuss the development and characterization of this system. [View Full Paper]

AAS 11 – 197

Architecture for Unconstrained 3-Axis Attitude Determination and Control Test Bed

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

A new approach for verification and validation (V&V) of attitude determination and control systems (ADCS) is presented. The proposed technique may significantly advance testing methodologies for responsive space missions and also provide a test bed for V&V of small satellite ADCS that is currently non-existent. Unlike the conventional approach, the proposed method uses a combination of a proprietary torque sensing platform and an attitude determination facility. The output of the torque sensors is used in the simulation of a spacecraft dynamic model on a computer. The attitude determination facility, which can be located remotely from the torque sensing platform, simulates a dynamic environment (e.g., star field) based on the output from the computer used by stationary sensors to determine the attitude. The approach also provides the ability to perform V&V of the ADCS hardware in thermal and vacuum environments.
[View Full Paper]

AAS 11 – 198

Full Performance Testing of Autonomous Star Sensors Under Laboratory Environment

Uwe Schmidt, **Boris Pradarutti** and **Klaus Michel**, AOCS Sensors, Jena-Optronik GmbH, Jena, Germany

The state of the art autonomous star sensors provide high quality attitude quaternion used for spacecraft control. The quaternion describes the rotation between the inertial reference frame in which the stars are reported and the present 3-axis attitude of the star sensor on board of the spacecraft. In contrast to classical star trackers, providing single star centroids only, an autonomous star sensor need to be stimulated with real star patterns in order to calculate the 3-axis attitude expressed in a quaternion. Jena-Optronik GmbH as manufacturer of star sensors continuously developed since 1980 the ground support equipment for star sensor qualification and acceptance testing. Based on the early ideas in 1990 which used high resolution electron tubes for star pattern imaging, Jena-Optronik designed a high precision optical star stimulator using LCD/OLED imaging technology which allows full performance testing of autonomous star sensors like ASTRO APS under laboratory environment. In addition, for the purpose of functional testing of star sensors, a compact optical stimulator head was developed which can be used in thermal-vacuum environment and/or for closed loop testing. The paper will present the technical principle of the optical stimulation and will show some test results derived from real laboratory star sensor tests. [View Full Paper]

AAS 11 – 199

HYDRA Star Tracker Innovative Test Solution

Yves Kocher, **Benoit Gelin**, **Damien Piot**, **Frédéric Gorog** and **Ludovic Blarre**, EADS-SODERN, Limeil-Brévannes, France

This paper will present the innovative test platform developed by Sodern for the qualification of Multiple Heads star tracker HYDRA. The HYDRA on-ground qualification was completed in 2010 including various types of tests, ranging from optical performance tests achieved with classical star simulators to more innovative multi-head software tests with the Mathlab-Simulink environment used to develop the application software. A description of the most innovative test platforms will be provided along with examples of HYDRA performance validation achieved with these test platforms. It will illustrate why these new test techniques are necessary to validate the enhanced performances of most sophisticated star trackers. [View Full Paper]

AAS 11 – 200

(Paper Withdrawn)

SESSION 14: ORBIT DETERMINATION AND NAVIGATION
Chair: Renato Zanetti, The Charles Stark Draper Laboratory

AAS 11 – 201

A Splitting Gaussian Mixture Method for the Propagation of Uncertainty in Orbital Mechanics

Kyle J. DeMars, Department of Aerospace Engineering and Engineering Mechanics, University of Texas at Austin, Texas, U.S.A.; **Robert H. Bishop**, College of Engineering, Marquette University, Milwaukee, Wisconsin, U.S.A.; **Moriba K. Jah**, GN&C Group, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

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

AAS 11 – 202

Analytical Non-Linear Propagation of Uncertainty in the Two-Body Problem

K. Fujimoto and **D. J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **K. T. Alfriend**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

Situational awareness of Earth-orbiting particles such as active satellites and space debris is highly important for future human activities in space. One topic of recent interest is the accurate and consistent representation of an observed object's uncertainty under non-linear dynamics. This paper is a survey of analytical non-linear propagation of uncertainty under two-body dynamics. In particular, we present ways to express, analytically and for all time, the probability distribution function (pdf) over state space, and the mean and variance-covariance matrix of the pdf. We also discuss some numerical examples. [View Full Paper]

AAS 11 – 203

Estimating a High-Resolution Lunar Gravity Field and Time-Varying Core Signature

Ryan S. Park, **Sami W. Asmar**, **Eugene G. Fahnestock**, **Alex S. Konopliv**, **Wenwen Lu** and **Mike M. Watkins**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

This paper presents the expected results of estimating a high-resolution lunar gravity field and time-varying tide and lunar core signatures using the measurements from the Gravity Recovery And Interior Laboratory (GRAIL) mission. An overall GRAIL mission capability is presented based on detailed error analysis of spacecraft dynamics and kinematics models, realistic DSN and inter-spacecraft tracking measurement uncertainties, and length of the data arcs. The largest source of dynamics un-modeled error comes from the spacecraft thermal radiation force, and in order to characterize its error contribution, an *a priori* error constraint model is derived based on orbit geometry and expected force magnitude. The result shows that estimating a lunar gravity field is robust against both dynamics and kinematics errors and a nominal field of degree 300 or better can be determined assuming a $2.5\times10^{-4}/n^2$ power law. The resolution of the gravity field is most sensitive to the inter-spacecraft Ka-band tracking accuracy. The core signature, however, is more sensitive to dynamic modeling errors and satisfying the latter science requirements depends on how accurately the spacecraft dynamics can be modeled. [View Full Paper]

AAS 11 – 204

Paper Withdrawn

AAS 11 – 205

Modification of Atmospheric Mass Density Model Coefficients Using Space Tracking Data – A Simulation Study for Accurate Debris Orbit Prediction

Jizhang Sang and **Craig Smith**, EOS Space Systems, Mt. Stromlo Observatory, Weston Creek, ACT 2611, Australia; **Kefei Zhang**, RMIT Space Research Center, RMIT City Campus, Melbourne, VIC 3001, Australia

The accuracy of the atmospheric mass density plays a critical role in the orbit prediction of LEO space objects. This paper presents a new method of improving the accuracy of computed mass density for the purpose of accurate orbit prediction of space debris objects over a short period of time. The method is based on simultaneous orbit determinations of multiple LEO space objects, where coefficients of the mass density model used for density computations are adjusted along with other parameters. The new method is investigated using simulated laser ranging observations, which are taken from a network of 9 ground tracking stations. In total 287 objects at altitude between 350 and 600km are chosen in the study, where 20~50 are used as calibration objects, and others as verification objects. The simulation results show that significant reduction of the orbit prediction errors for 7 day prediction period is achieved. [View Full Paper]

AAS 11 - 206
(Paper Withdrawn)

AAS 11 – 207

Sensitivity of Magnetospheric Multi-Scale (MMS) Mission Navigation Accuracy to Major Error Sources

Corwin Olson and **Anne Long**, a.i. solutions, Inc., Lanham, Maryland, U.S.A.; **J. Russell Carpenter**, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

The Magnetospheric Multiscale (MMS) mission consists of four satellites flying in formation in highly elliptical orbits about the Earth, with a primary objective of studying magnetic reconnection. The baseline navigation concept is independent estimation of each spacecraft state using GPS pseudorange measurements referenced to an Ultra Stable Oscillator (USO) with accelerometer measurements included during maneuvers. MMS state estimation is performed onboard each spacecraft using the Goddard Enhanced Onboard Navigation System (GEONS), which is embedded in the Navigator GPS receiver. This paper describes the sensitivity of MMS navigation performance to two major error sources: USO clock errors and thrust acceleration knowledge errors. [View Full Paper]

SESSION 15: SATELLITE RELATIVE MOTION
Chair: Dr. Aaron Trask, Apogee Integration

AAS 11 – 208
A Virtual-Time Method for Modeling Relative Motion of Noncircular Satellites

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

The Hill-Clohessy-Wiltshire equations describe the motion of a deputy satellite in close proximity to a circular chief. This paper presents an extension of the Hill-Clohessy-Wiltshire equations to elliptic chiefs by a virtual-time approach. The relative position at each instant is approximated by evaluating the Hill-Clohessy-Wiltshire solution at a virtual time. Therefore, the shape of the trajectory is approximated using an Hill-Clohessy-Wiltshire trajectory, but the progress along the trajectory is modified to account for the chief's eccentricity. Example solutions for the virtual time are calculated, and the errors of the Hill-Clohessy-Wiltshire and virtual-time solutions are compared. [View Full Paper]

AAS 11 – 209
Closed-Form Solutions for Satellite Relative Motion in an Axially-Symmetric Gravitational Field

Vladimir Martinuşi and **Pini Gurfil**, Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

A different approach is proposed for the study of satellite relative motion in an axially-symmetric gravitational field. Instead of using the Keplerian motion as the generating nominal orbit for the absolute motion, another "unperturbed" orbit is proposed instead: An equatorial orbit about an oblate planet. Based on the superintegrability of such motion, closed-form solutions for the equatorial relative motion are obtained. Analytic conditions for the periodicity of the relative motion in a generic central force field are presented, and utilized to design long-term bounded relative motion under high-order even zonal perturbations. [View Full Paper]

AAS 11 – 210

Cluster Flight for Fractionated Spacecraft

Leonel Mazal and Pini Gurfil, Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

Fractionated spacecraft constitutes a satellite design methodology wherein the functional capabilities of a single monolithic satellite are distributed among multiple free-flying, wirelessly-communicating modules. One of the main challenges of a fractionated spacecraft system is cluster flight, i.e. keeping the various modules within a bounded distance, typically less than 100 km, for the entire mission lifetime. This paper presents a methodological development of cluster flight algorithms for fractionated spacecraft systems. To obtain distance-bounded relative motion, a new constraint on the initial conditions of the modules is developed. A concomitant analytical bound on the relative distance between the modules is proven based on a design model assuming time-invariance of the environmental perturbations. It is then shown that if the actual astrodynamical model includes other, possibly time-varying effects, mild drifts between the modules are obtained. Furthermore, this paper presents a cluster establishment algorithm for tracking a given nominal orbit, whose characteristics satisfy the previously-develop no-drift constraint. This algorithm provides fuel balancing among the maneuvering modules as well as minimization of the total fuel consumption. Numerical simulations using realistic astrodynamical models are used to validate the analysis.
[View Full Paper]

AAS 11 – 211

Relative Motion Modeling and Control in a Perturbed Orbit

Mohamed Okasha and **Brett Newman**, Department of MAE, Old Dominion University, Norfolk, Virginia, U.S.A.

In this paper, the dynamics of the relative motion problem in a perturbed orbital environment are exploited based on Gauss' and Cowell's variational equations. The inertial coordinate frame and relative coordinate frame (Hill frame) are studied to describe the relative motion. A linear high fidelity model is developed to describe the relative motion. This model takes into account primary gravitational and atmospheric drag perturbations. In addition, this model is used in the design of a control, guidance, and navigation system of a chaser vehicle to approach towards and to depart form a target vehicle in proximity operations. Relative navigation uses an extended Kalman filter based on this relative model to estimate the relative position and velocity of the chaser vehicle with respect to the target vehicle. This filter uses the range and angle measurements of the target relative to the chaser from a simulated LIDAR system. The corresponding measurement models, process noise matrix, and other filter parameters are provided. Numerical simulations are performed to assess the precision of this model with respect to the full nonlinear model. The analyses include the navigations errors and trajectory dispersions. [View Full Paper]

AAS 11 – 212

Relative Motion Guidance, Navigation and Control for Autonomous Spacecraft Rendezvous

Mohamed Okasha and **Brett Newman**, Department of MAE, Old Dominion University, Norfolk, Virginia, U.S.A.

In this paper, the development of guidance, navigation, and control algorithms of an autonomous space rendezvous and docking system are presented. These algorithms are based on using the analytical closed-form solution of the Tschauner-Hempel equations that is completely explicit in time. The navigation system uses an extended Kalman filter based on Tschauner-Hempel equations to estimate the relative position and velocity of the chaser vehicle with respect to the target vehicle. This filter uses the range and angle measurements of the target relative to the chaser from a simulated LIDAR system. The corresponding measurement models, process noise matrix and other filter parameters are provided. The guidance and control algorithms are based on the glideslope used in the past for rendezvous and proximity operations of the Space Shuttle with other vehicles. These algorithms are used to approach, flyaround, and to depart form a target vehicle in elliptic orbits. The algorithms are general and able to transfer the chaser vehicle in any direction, decelerate while approaching the target vehicle, and accelerate when moving away. Numerical nonlinear simulations that illustrate the relative navigation, guidance and control algorithms performance and accuracy are evaluated in the current paper. [View Full Paper]

AAS 11 – 213

Satellite Formation Design Using Primer Vector Theory

Weijun Huang, Department of Mechanical and Aerospace Engineering, University of Missouri-Columbia, Columbia, Missouri, U.S.A.

Estimating fuel consumption for each satellite is important for designing a satellite formation. Parametric solutions of the Clohessy-Wiltshire (CW) equations are widely used to design basic elliptic formation (BEF), which can be viewed as a basic building block of a more complicated formation. In this paper, linear primer vector theory is used to study the problem of designing a coplanar target BEF for a known BEF. Lemmas and theorems that lead to an optimal design of a target BEF are proved. This research surprisingly reveals the advantage of using primer vector theory on the formation design problem involving maneuverability. [View Full Paper]

AAS 11 – 214

The Virtual-Chief Method for Modeling Relative Motion of Noncircular Satellites

Ryan E. Sherrill and **Andrew J. Sinclair**, Department of Aerospace Engineering, Auburn University, Auburn, Alabama, U.S.A.; **T. Alan Lovell**, Space Vehicles Directorate, U.S. Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.; **Kirk W. Johnson**, Performance Analysis and Software Branch, Missile Defense Agency, Kirtland AFB, New Mexico, U.S.A.; **Douglas D. Decker**, Science Applications International Corporation, Wright-Patterson AFB, Ohio, U.S.A.

The Hill-Clohessy-Wiltshire equations are often used for preliminary mission design to model the relative motion between two satellites. The virtual-chief method described in this paper is a modification to the classic Hill-Clohessy-Wiltshire equations for chief satellites of non-zero eccentricity. A kinetics-based method for determining the initial conditions is also developed. Results compare the error and relative-motion trajectory of the Hill-Clohessy-Wiltshire and the virtual-chief method to Kepler's two-body motion to demonstrate the validity of this method. [View Full Paper]

SESSION 16: SPECIAL SESSION: OPTICAL NAVIGATION
Chair: Dr. William Owen, Jet Propulsion Laboratory

AAS 11 – 215

Methods of Optical Navigation

William M. Owen, Jr., Optical Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Optical navigation is the use of onboard imaging to aid in the determination of the spacecraft trajectory and of the targets' ephemerides. Opnav techniques provide a direct measurement of the direction from a spacecraft to target bodies. Opnav data thus complement both radiometric tracking data (for instance, Doppler and range) and the ground-based astrometry which is used to determine the *a priori* ephemeris of the targets. We present the geometry and camera models which form the mathematical basis for optical navigation and some of the image processing techniques by which one can extract the optical observables—that is, the sample and line coordinates of images—from pictures. [View Full Paper]

AAS 11 – 216

Optical Navigation Planning Process for the Cassini Solstice Mission

Simon Nolet, **Stephen D. Gillam** and **Jeremy B. Jones**, Jet Propulsion Laboratory, Pasadena, California, U.S.A.

During the Cassini Equinox Mission, the Optical Navigation strategy has gradually evolved toward maintenance of an acceptable level of uncertainty on the positions of the bodies to be observed. By counteracting the runoff of the uncertainty over time, this strategy helps satisfy the spacecraft pointing requirements throughout the Solstice Mission, while considerably reducing the required imaging frequency. Requirements for planning observations were established, and the planning process itself was largely automated to facilitate re-planning if it becomes necessary. This paper summarizes the process leading to the optical navigation schedule for the seven years of the Solstice Mission. [View Full Paper]

AAS 11 – 217

Optical Navigation for the Epoxi Mission

Brian P. Rush, **William M. Owen, Jr.**, **Shyam Bhaskaran** and **Stephen P. Synnott**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Deep Impact spacecraft flew by comet Hartley 2 on November 4, 2010 as part of its extended mission called EPOXI. Successful navigation depended critically on the quality and timing of optical navigation data processing, because pictures of the comet provided the most precise comet-relative position of the spacecraft. This paper describes the planning, including the picture timing and pointing; the methods used to determine the center of the comet image in each picture; and the optical navigation results, which provided the necessary information to allow the cameras to accurately target the comet for science imaging at encounter. [View Full Paper]

AAS 11 – 218

New Horizons Jupiter Data Analysis: Examining the Jovian System Using Optical Navigation Software

Dylan O'Connell, Department of Physics, Tufts University, Medford, Massachusetts, U.S.A.; **William M. Owen, Jr.**, Optical Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The *New Horizons* spacecraft, bound for a Pluto encounter in 2015, acquired over 1000 pictures of Jupiter and its satellites during a 2007 gravity assist maneuver using its Long-Range Reconnaissance Imager (LORRI). We analyzed a subset of pictures containing satellites in order to improve their ephemerides using optical navigation techniques. Additionally, a sequence of images of Callirrhoe, one of Jupiter's outermost satellites, was taken by LORRI as part of an optical navigation test. This paper describes the results of our geometric camera calibration and analysis of the test sequence.
[View Full Paper]

AAS 11 – 219

Post-Flight Lunar Landing-Site Localization and Reconstruction Using Descent Camera Imagery

J. Ed Riedel, **Andrew Vaughan**, **Mike Wang** and **Nickolaos Mastrodemos**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

This paper describes a process for reconstruction of the surface position of a landed lunar spacecraft by use of descent imagery. Reconstruction of the landed location is necessary to provide both scientific context of the science obtained from a lander, and to compute the ascent and Earth return trajectory for a mission that would return samples, such as the Moonrise proposal. The method was developed using two system models 1) LCROSS descent (pre-impact) images, comparing with the radio-metric ground truth, and 2) Simulations of the potential Moonrise landing trajectory and lunar terrain, utilizing camera simulations of the Moonrise imager as it would be used during descent. Two methods are used for computing the trajectory, and resultant landing site, the AutoNav onboard navigator, which forms the "N" component of AutoGNC, and the Optical Navigation Program (ONP), which forms the core of JPL's ground-based optical navigation system. This paper describes the methodology of the estimation process, and gives LCROSS results from real data, and results based on the simulations for the Moonrise proposal. [View Full Paper]

AAS 11 – 220

Optical Navigation Near Small Bodies

Robert W. Gaskell, Planetary Science Institute, Tucson, Arizona, U.S.A.

Optical navigation is a crucial component of orbit determination for spacecraft operations around a small body. Precise image-space locations of fixed points on the body are combined with Doppler measurements to unambiguously determine the spacecraft's position. A landmark "maplet" can be located in images under a wide range of illuminations, resolutions and viewing geometry. Maplets are digital topography/albedo representations of pieces of the body's surface constructed by a process called stereophotoclinometry. They are also used to determine the body's global shape and topography. We shall discuss the construction of maplets and strategies to optimize navigation and surface characterization. [View Full Paper]

AAS 11 – 221

Evaluation and Improvement of Passive Optical Terrain Relative Navigation Algorithms for Pinpoint Landing

Yang Cheng, **Daniel Clouse**, **Andrew Johnson**, **William Owen** and **Andrew Vaughan**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

Future solar system in situ exploration will deploy a pin-point landing (PPL) capability, which is defined as the capability of landing a spacecraft within 100 meters of a targeted site. PPL provides safe and affordable access to high scientific targets, allows the highest science returns, and reduces risk to the spacecraft. PPL relies on computer vision based terrain relative navigation (TRN) technology. This technology recognizes the local terrain and locates the spacecraft within the local terrain frame. Currently, both active sensing (radar or lidar) and passive sensing technologies are actively pursued. In this paper we will focus on passive optical TRN, which compares a descent image with an on-board reference map to locate the spacecraft during descending. First, we present the findings from evaluating two algorithms: MAIA and OBIRON using imagery collected during a field test campaign in 2008. Then we point out the strengths and weaknesses of both algorithms and then suggest some modifications to the algorithms to improve performance. Finally, we give a brief report of the performance of the modified TRN algorithm that is based on a modular TRN toolkit that merges the algorithm components from MAIA and OBIRON. [View Full Paper]

AAS 11 – 222

Optical Navigation for Dawn at Vesta

Nickolaos Mastrodemos, **Brian Rush**, **Drew Vaughan** and **Bill Owen**, Optical Navigation Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

The Dawn S/C, launched in September 2007, towards Vesta and Ceres, will enter into orbit about asteroid Vesta in July 2011 and will conduct science remote sensing operations for approximately one year at various orbital altitudes. Vesta navigation operations begin with early approach in May 2011 until departure to Ceres in July 2012. A key navigation aspect is optical navigation, which will be conducted at all mission phases. Here we review the optical navigation plan, imaging, methodology, data types, as well as expected performance in the context of the overall mission navigation. A key aspect of optical navigation at Dawn that will receive particular attention is the extensive use of landmark navigation during most of mission phases. In addition to supporting real-time navigation operations, optical navigation will be used to determine some key physical characteristics of Vesta, such as the asteroid's pole & shape, to assist mission design & science operations. [View Full Paper]

SESSION 17: SATELLITE CONSTELLATIONS
Chair: Dr. Matthew Wilkins, Schafer Corporation

AAS 11 – 223

Application of UKF in Autonomous Orbit Determination of Navigation Constellation

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

The autonomous orbit determination of navigation constellation has been explored by the US since 1980. The core of the scheme is using the two-way range measurement and the data obtained from cross-link communication as inputs of distributed Kalman Filter to estimate satellite orbit. The method approximates the nonlinear system by linearization which directly influences the precision of estimation. Recently, a new nonlinear filter named Sigma Point Kalman Filter which is convenient to use and more precise has become a new favorite estimation technique. It has been widely applied in target tracking, data fusion and so on. In this article, the autonomous Orbit Determination algorithm based on Unscented Kalman Filter which is one special kind of SPKF is proposed. Besides, the application of standard UKF, SSUKF which is based on spherical simplex sigma-point and Modified SSUKF on autonomous OD of navigation constellation is detailed analyzed. Simulation results show that the selected nonlinear estimation algorithms can maintain the long term autonomous orbit determination and the application of SSUKF in autonomous OD of constellation indeed reduces the computation cost while the performance remains almost the same. It is also proved that the modified SSUKF is the best in all three algorithms compared and it can restrict filter divergence caused by the non-observable error of satellite initial orbit. In one word, the method explored in this article could be a new solution to the autonomous orbit determination of navigation constellations and it could be a foundation of further study on such research field. [View Full Paper]

AAS 11 – 224
(Paper Withdrawn)

AAS 11 – 225

Linear Stability and Shape Analysis of Spinning Three-Craft Coulomb Formations

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

This paper describes the discovery of families of multiple invariant shape solutions for collinear three-craft Coulomb formations with set charges, as well as the results of linear stability analysis on such formations. The charged spacecraft are assumed to be spinning about each other in deep space without relevant gravitational forces present. Up to three invariant shape solutions are possible for a single set of craft charges. This behavior, only speculated in previous work, is confirmed through analysis and numerical simulation examples. In fact, distinct regions are analytically described where two or three invariant shape solutions exist for a single charge set. These regions are analyzed to determine what range of trajectories are possible. Linear stability analysis yields the first examples of marginally stable three-craft invariant shape formations. Linearly stable behavior is only observed when two invariant shape solutions result for one set of charges, where one shape will be unstable and the other marginally stable. Numerical simulation illustrates stability for ten orbital periods. [View Full Paper]

AAS 11 – 226

Necklace Theory on Flower Constellations

Daniel Casanova, Science Faculty, Grupo de Mecánica Espacial-IUMA, Universidad de Zaragoza, Spain; **Martín Avendaño**, Visiting Assistant Professor, Math Department, Texas A&M University, College Station, Texas, U.S.A.; **Daniele Mortari**, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.

Theory of Flower Constellations has been improved with the 2-D and 3-D Lattice Flower Constellations. However, placing a satellite in each admissible location is not an optimal way to design a constellation. The necklace theory considers constellations whose satellites are subsets of the satellites of a Lattice Flower Constellation, keeping all its symmetries, in order to reduce the cost of the mission. Mathematically, these subsets are parameterized by necklaces (describing which satellites in the first orbit of the underlying constellation we keep), and a shifting parameter that controls the phasing between subsequent orbits. [View Full Paper]

AAS 11 – 227

On-Orbit Servicing of Satellites in Circular Constellation Using a Single Service Vehicle

Atri Dutta, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta Georgia, U.S.A.

In this paper, we consider the problem of determining the optimal way of servicing (delivering fuel and other commodities) multiple satellites, moving in a circular orbit, by a single service vehicle. We assume that the servicer employs a chemical propulsion system. We develop a formulation that allows the consideration of a general objective function taking into account both servicing time and fuel expenditure. The formulation also allows for inclusion of fuel budget and time constraints. We present numerical results for sample constellations, and demonstrate the impact of choice of objective and constraints on the optimal solution. [View Full Paper]

AAS 11 – 228

Optimization of Hybrid-Orbit Constellation Servicing for Constellations

Zhongxing Tang and **Chao Han**, School of Astronautics, Beihang University, Beijing, China

The hybrid-orbit constellation is proposed to perform the servicing mission for the constellation which needs on-orbit servicing operations. The objective of such hybrid-orbit constellation is to service as many as possible with the restrictions of the satellite's transfer time and fuel cost. Tent-map chaotic particle swarm optimization (TCPSO) is adopted to optimize the optimal fuel problem for Lambert orbital maneuver, and then used again to optimize the orbital slots in the hybrid-orbit constellation. The numerical simulation shows that the hybrid-orbit constellation has a better servicing ability to service for all the satellite of the constellation. [View Full Paper]

AAS 11 – 229

Optimizing Spacecraft Placement for Liaison Constellations

C. Channing Chow, Department of Astronautical Engineering, University of Southern California, Los Angeles, California; **Benjamin F. Villac**, Department of Mechanical and Aerospace Engineering, University of California, Irvine, California, U.S.A.; **Martin W. Lo**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

A navigation and communications network is proposed to support an anticipated need for infrastructure in the Earth-Moon system. Periodic orbits will host the constellations while a novel, autonomous navigation strategy will guide the spacecraft along their path strictly based on satellite-to-satellite telemetry. In particular, this paper investigates the second stage of a larger constellation optimization scheme for multi-spacecraft systems. That is, following an initial orbit down-selection process, this analysis provides insights into the ancillary problem of spacecraft placement. Two case studies are presented that consider configurations of up to four spacecraft for a halo orbit and a cycler trajectory. [View Full Paper]

AAS 11 – 230

Peer-to-Peer Servicing of Satellites in Circular Constellation

Atri Dutta, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta Georgia, U.S.A.

During the Peer-to-Peer (P2P) phase of a mixed servicing strategy, a set of satellites (already serviced by a service vehicle) redistribute their resources (fuel and other commodities) among other satellites, by engaging in P2P maneuvers. In this paper, we consider the P2P problem for multiple satellites moving in a circular orbit, and employing chemical propulsion system. We develop an integer programming based formulation that considers minimization of a general objective taking into account both P2P maneuver time and fuel expenditure. The optimization framework also includes fuel budget and time constraints. We demonstrate our methodology by presenting numerical examples. [View Full Paper]

SESSION 18: LOW-THRUST TRAJECTORY DESIGN
Chair: Ryan Park, Jet Propulsion Laboratory

AAS 11 – 231

A Simple Method for Improving Recovery Characteristics of Fuel Optimal Low-Thrust Transfers

Iman Alizadeh and **Benjamin Villac**; Department of Mechanical and Aerospace Engineering, University of California, Irvine, California, U.S.A.

This paper aims at designing recoverable low-thrust trajectories subject to temporary engine failure. The recoverable trajectory is obtained by backward propagation of an optimal trajectory with a prescribed recovery time. Comparison of the life-time between the optimal and recoverable trajectories shows reduction of the impact risk for recoverable trajectories in case of temporary engine loss. The simplicity of the proposed algorithm allows trajectory designers to quickly generate and analyze increased life-time trajectories. The optimality of the recoverable trajectories is investigated analytically by formulating a sequential optimal control problem. The concepts are illustrated in the Jupiter-Europa system for two transfer scenarios. This method has an advantage that the optimal retargeting trajectories after engine recovery, lie on a single optimal trajectory. The cost of retargeting the final state after engine recovery can be computed for the whole trajectory by solving only a single optimal control problem. [View Full Paper]

AAS 11 – 232

Model Predictive Feedback Control Strategy for Low Thrust Spacecraft Interplanetary Missions

Joseph A. Starek and **Ilya V. Kolmanovsky**, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Michigan, U.S.A.

The use of Model Predictive Control (MPC)-based strategy is considered for spacecraft interplanetary transfer maneuvers with low thrust propulsion. Two nonlinear MPC approaches, each employing variations of the same optimization framework, are investigated. As a specific example, an Earth-to-Mars coplanar heliocentric transfer problem is studied. A comparison is made between the MPC law and the open-loop optimized trajectory in terms of fuel consumption, transfer time, and ability of the spacecraft to follow an optimal trajectory under the influence of orbital perturbations and control disturbances. [View Full Paper]

AAS 11 – 233

Low-Thrust Transfers With Earth-Shadow and Power-Degradation Effects

Craig A. Kluever, Department of Mechanical and Aerospace Engineering, University of Missouri-Columbia, Columbia, Missouri, U.S.A.

Optimizing low-thrust Earth-orbit transfers is a challenging problem due to the low control authority of the electric thrusters, and consequently the long transfer times. This already challenging problem is exacerbated when real environmental effects associated with operating electric-propulsion spacecraft, such as Earth-shadow eclipses (zero thrust) and solar-cell degradation (due to trapped radiation), are included. In many cases, mission analysts need to perform preliminary trade studies in order to determine the general trend among various electric-propulsion system parameters. This paper presents a new low-thrust trajectory program that can easily accommodate both Earth-shadow and power-degradation effects. The new method utilizes Edelbaum's analytic solutions for continuous-thrust, quasi-circular transfers, and hence does not require numerical integration of the system dynamics. Furthermore, the method does not rely on an iterative search, so non-convergence is not an issue. Several numerical trials are presented in order to demonstrate the utility of the new low-thrust trajectory program as a useful tool for rapidly performing mission analyses and trade studies. [View Full Paper]

AAS 11 – 234

Optimum Low-Thrust Elliptic Transfer for Power Limited Spacecraft Using Numerical Averaging

Zahi Tarzi, **Jason Speyer** and **Richard Wirz**, Department of Mechanical/Aerospace Engineering, University of California, Los Angeles, California, U.S.A.

Low-thrust electric propulsion is increasingly being used for spacecraft missions due to its high propellant efficiency, which permits larger payloads for a given mission delta-V. As a result, trajectory optimization for low-thrust missions is becoming increasingly important. However, there are few medium and low fidelity low-thrust trajectory tools available for use in preliminary mission design studies. This paper describes a quick method for obtaining such preliminary trajectories for transfers which involve many revolutions about the primary body. This paper considers variable thrust transfers using a first order averaging method to obtain the fuel optimum rates of change of the equinoctial orbital elements in terms of each other and the Lagrange multipliers. The advantages of using variable thrust are analyzed with comparisons to the results of constant thrust methods. Constraints on maximum thrust and power as well as minimum periapsis are implemented and the equations are averaged numerically using a 10th order Gausian quadrature. The method also accounts for J2 effects and shadowing. A shooting method is used to solve the optimization problem numerically based on an initial guess. The use of numerical averaging allows for more complex gravity perturbations to be added in the future without great difficulty. A few example elliptic orbit transfers with the Earth as the central body are analyzed. [View Full Paper]

AAS 11 – 235

Low-Thrust Transfer Between Jovian Moons Using Manifolds

Keita Tanaka, Department of Aeronautics and Astronautics, University of Tokyo, Japan; **Jun'ichiro Kawaguchi**, Institute of Space and Astronautical Science/JAXA, Sagamihara, Kanagawa, Japan

The development of electric propulsion systems such as ion engines has brought low-thrust control into practical use. This has made the design of spacecraft trajectories with low continuous thrust more and more demanding. This work concerns low-energy transfer trajectories between the Jupiter satellites using effectively the n-body dynamics in the Jupiter system and low-thrust controls. To analyze the dynamics of n-body models, we use the three-body problem as a model and apply the patched three-body approximation. We also use invariant manifold tubes and the result provides how to connect two different manifolds with low-thrust, low-energy trajectories. [View Full Paper]

AAS 11 – 236

Extension of the Molniya Orbit Using Low-Thrust Propulsion

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

Extension of the standard Molniya orbit using low-thrust propulsion is presented. These newly proposed, highly elliptical orbits are enabled by existing low-thrust propulsion technology, enabling new Earth Observation science and offering a new set of tools for mission design. In applying continuous low-thrust propulsion to the conventional Molniya orbit the critical inclination may be altered from the natural value of *63.4deg*, to any inclination required to optimally fulfill the mission goals. Analytical expressions, validated using numerical methods, reveal the possibility of enabling a Molniya orbit inclined at *90deg* to the equator. Fuel optimal low-thrust control profiles are then generated by the application of pseudo spectral numerical optimization techniques to these so-called Polar-Molniya orbits. These orbits enable continuous, high elevation visibility of the Frigid and Neighboring Temperate regions, using only two spacecraft compared with six spacecraft required for coverage of the same area with a conventional Molniya orbit. This can be achieved using existing ion engines, meaning no development in technology is required to enable these new, novel orbits. Order of magnitude mission lifetimes for a range of mass fractions and specific impulses are also determined, and are found to range from 1.2 years to 9.4 years. Where, beyond 9.4 years the outline mass budget analysis for spacecraft of initial masses of 500kg, 1000kg and 2500kg, illustrated there is no longer a capacity for payload for all initial mass of spacecraft. [View Full Paper]

AAS 11 – 237
(Paper Withdrawn)

AAS 11 – 238

Fourth Order Expansions of the Luni-Solar Gravity Perturbations Along Rotating Axes for Trajectory Optimization

Jean A. Kéchichian, Astrodynamics Department, The Aerospace Corporation, El Segundo, California, U.S.A.

A fourth order extension of the analytic form of the accelerations due to the luni-solar gravity perturbations along rotating axes is presented. These derivations are carried out in order to increase the accuracy of the dynamic modeling of perturbed optimal low-thrust transfers between general elliptic orbits, and enhance the fidelity of trajectory optimization software used in simulations and mission analyses. A set of rotating axes attached to the thrusting spacecraft is used such that both the thrust and perturbation accelerations due to Earth's geopotential and the luni-solar gravity are mathematically resolved along these axes prior to numerical integration of the actual trajectory. This Gaussian form of the state as well as the adjoint differential equations form a set of equations that are readily integrated in a most efficient manner for rapid iterations and ultimate convergence to a desired transfer. This analysis further reveals that further extensions to higher orders, say to the fifth order and beyond, are not needed to extract even more accuracy in the solutions because the minimum-time transfer solutions become fully stabilized in the sense that they do not exhibit any differences beyond a fraction of a second, or at most a few seconds even in the more extreme cases of very large orbits with apogee heights around 100,000 km with strong lunar influence.
[View Full Paper]

SESSION 19: EARTH ORBIT AND MISSIONS
Chair: Dr. Xiaoli Bai, Texas A&M University

AAS 11 – 239

Deep Resonant GPS-Dynamics Due to the Geopotential

Martin Lara, Real Observatorio de la Armada, San Fernando, Spain; **Juan F. San-Juan**, Universidad de La Rioja, Logroño, Spain; **Zachary J. Folcik**, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.; **Paul J. Cefola**, University at Buffalo, State University of New York, Amherst, New York, U.S.A.

On time scales of interest for mission planning of GNSS satellites, the qualitative motion of the semi-major axis and the node evolves primarily from resonances with the Earth's gravitational field. The relevant dynamics of GPS orbits, which are in deep 1 to 2 resonance, is modeled with an integrable intermediary that depends only on one angle, the stroboscopic mean node, plus a two degrees of freedom perturbation that is factored by the eccentricity. Results are compared with long-term runs of the GTDS DSST showing very good agreement. [View Full Paper]

AAS 11 – 240

Effect of Density Model Time-Delay Errors on Orbit Prediction

Rodney L. Anderson, **Christian P. Guignet**, **George H. Born**, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, U.S.A.;
Jeffrey M. Forbes, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.

This study examines the effects of density model time-delay errors by focusing on the CHAMP spacecraft data over the 2003-2007 time period. The data is first analyzed to determine the magnitudes of time delays encountered when using a density model. The analysis is initiated by examining the effects of the expected delays of one to three hours on a theoretical density profile. Delays are then introduced into the model and actual density profile for multiple different cases, and the effects on the orbit prediction results are examined. It is found that the effects are potentially significant for the applications of interest in this study. [View Full Paper]

AAS 11 – 241
(Paper Withdrawn)

AAS 11 – 242

Hypersonic, Aerodynamically Controlled, Path Constrained Reentry Optimization in SOCS

Christopher L. Ranieri, Flight Mechanics Department, The Aerospace Corporation, El Segundo, California, U.S.A.

Hypersonic, aerodynamically controlled reentries have been optimized with the SOCS optimization software package. The reentries incorporate various path constraints on the controls and states along with interior waypoint constraints. These constraints address heating, stability, and recession/ablation issues along with no-fly zones. SOCS was used to determine the capabilities of the new reentry vehicle and supplemented the work performed by TOP, a separate, simpler, trajectory optimization program that was used for most of the reentries examined. SOCS provided more detailed analysis for trajectories too complicated for TOP. These stressing trajectories involved various flight regimes and durations, highlighting the dynamic environments experienced during hypersonic reentries. SOCS was used in an iterative process with various subsystem experts to shape the reentries to optimize heating, recession, and stability performance.
[View Full Paper]

AAS 11 – 243

On-Orbit Range Computation Using Gauss' Variational Equations With J_2 Perturbations

Marcus J. Holzinger and **Daniel J. Scheeres**, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, U.S.A.; **R. Scott Erwin**, Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, New Mexico, U.S.A.

Aircraft range is an intuitive measure that provides strategic and tactical insight to the end user. Currently there is no rigorously defined and derived range measure for on-orbit spacecraft operations with which to inform strategic decisions and planning. This paper illustrates how range may be computed in the context of orbital motion using optimal control theory and how existing results in reachability set computation may be leveraged. The solution method presented incidentally solves the free-time, minimum-impulse full orbit element transfer problem under J2 perturbations. Numerical examples of on-orbit range are given and their application to spacecraft operations detailed. [View Full Paper]

AAS 11 – 244
(Paper Withdrawn)

AAS 11 – 245

TerraSAR-X / TanDEM-X Formation Acquisition – Analysis and Flight Results

Ralph Kahle, **Benjamin Schlepp**, **Florian Meissner**, **Michael Kirschner** and **Reinhard Kiehling**, German Space Operations Center, German Aerospace Center, Wessling, Germany

This paper summarizes the work performed in the fields of TanDEM-X (TDX) launch injection collision assessment, target orbit acquisition analysis and in-flight realization of the formation acquisition with the already flying TerraSAR-X (TSX). The first two topics were essential in the process of TDX launch day selection in order to minimize both the risk of collision and the maneuver budget. Here risk of collision refers to the danger of close approach between TSX and the newly injected Dnepr upper-stage, the gas dynamic shield, and the TDX. Furthermore, the analytical approach to estimate the TDX total velocity increment required for the acquisition of the formation with TSX is discussed including a presentation of the results that characterize the maneuver budget as a function of launch day and launch injection accuracy. The formation acquisition strategy was numerically estimated for the confirmed launch date considering operational constraints and recent TSX orbit evolution. After TDX launch only minor changes to the pre-launch maneuver sequence became necessary especially due to unforeseen space debris avoidance maneuvers within the first days of the mission. Besides the description of the formation acquisition process, this paper also depicts the formation reconfiguration process from wide into narrow formation performed in October 2010. The successful acquisition of the close formation was the start of the common TSX / TDX instrument operation for purpose of bi-static commissioning.
[View Full Paper]

AAS 11 – 246

Trajectory Reconstruction of the Ikaros DCAM2

Andrew T. Klesh, **Osamu Mori**, **Hirotaka Sawada**, **Yuichi Tsuda**, JAXA, Sagamihara, Kanagawa, Japan; **Sabro Matunaga**, Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, Tokyo, Japan; **Shinichi Kimura**, Department of Electrical Engineering Faculty of Science and Technology, Tokyo University of Science, Tokyo, Japan

After deployment of the IKAROS solar sail in June 2010, a small ejectable camera, DCAM2, was released from the spacecraft to provide external imagery and verification of full sail deployment. In this paper we analyze the images taken by the DCAM imager and attempt to use them as a measurement source to supplement the known initial parameters to reconstruct the trajectory of the micro-spacecraft. Further complicating this analysis is the requirement that IKAROS is required to spin to maintain sail shape. Though spinning stretches the sail flat, the sail is also warped due to the solar pressure exerted upon it. The second goal of the analysis is to attempt to estimate the warping of the sail due to this pressure. The contributions of this paper cover several areas: 1) A method is provided to reconstruct the DCAM imager trajectory using a small number of photos as the sole measurement device; 2) An estimate of sail warping is provided giving some indication of total solar pressure enacted upon the sail; 3) Recommendations for the design of future external imagers of solar sails and other structures are given based on the difficulties in carrying out this analysis. [View Full Paper]

SESSION 20: DYNAMICAL SYSTEMS AND ORBITAL MECHANICS

Chair: Dr. Kathleen Howell, Purdue University

AAS 11 – 247

Dynamics At Cusp Points on the Repeating Orbits

Mohammed Ghazy, Department of Engineering, Math and Physics, University of Alexandria, Alexandria, Egypt; **Brett Newman**, Department of Aerospace Engineering, Old Dominion University, Norfolk, Virginia, U.S.A.

Cusp curves are formulated when a repeating orbit touches its zero velocity curve in a synodic coordinate system. Dynamics at cusp points are studied and a dynamical system approach is introduced to solve for the variations and then compared with the known power series solution. A proposed direct-repeating configuration in which a spacecraft on a direct orbit can maneuver about another vehicle on a retrograde orbit is introduced. [View Full Paper]

AAS 11 – 248

(Paper Withdrawn)

AAS 11 – 249
(Paper Withdrawn)

AAS 11 – 250

Lagrangian Coherent Structures in the Restricted Three-Body Problem

Cody R. Short and **Kathleen C. Howell**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Xavier M. Tricoche**, Department of Computer Science, Purdue University, West Lafayette, Indiana, U.S.A.

The inherent difficulty of spacecraft mission design in regimes involving multiple gravitating bodies is somewhat alleviated by tools that provide sophisticated conceptual cues in an understandable format. Specifically, the concepts of the Finite-Time Lyapunov Exponent (FTLE) and Lagrangian Coherent Structures (LCS) are employed to visually identify regions characterized by certain behavior in a system, or to effectively isolate trajectories of potential use. The Restricted Three-Body Problem (R3BP) is a dynamical system that displays both ordered and chaotic behavior. This varied complexity is amenable to visual analysis of FTLE information and the associated LCS. Samples of FTLE/LCS visualizations highlight the applicability of these tools for mission design.
[View Full Paper]

AAS 11 – 251

Three-Impulse Rendezvous Near Circular Orbit Determined Through a New Primer Vector Analysis

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

A new approach is presented for the optimal impulsive rendezvous of a spacecraft in an inertial frame near a circular orbit. Using a form of primer-vector theory the problem is formulated in a way that leads to relatively easy calculation of the optimal velocity increments. A certain vector that can easily be calculated from the boundary conditions determines the number of impulses required for solution of the optimization problem and also is useful in the computation of these velocity increments.

This first of three papers on this subject concentrates on those problems that require three non-degenerate nonsingular impulses for optimal rendezvous. Necessary and sufficient conditions for boundary conditions to require exactly three nonsingular non-degenerate impulses for solution of the optimal rendezvous problem, and a means of calculating these velocity increments are presented. If necessary these velocity increments could be calculated from a hand calculator containing trigonometric functions. A simple example of a three-impulse rendezvous problem is solved and the resulting trajectory is depicted.

Although this approach is thought to provide simpler computations than existing methods, its main contribution, as presented in this and the following papers, may be in unifying and understanding the role of degenerate, non-degenerate, and singular solutions in the structure of solutions of impulsive rendezvous problems associated with the restricted two-body problem. [View Full Paper]

AAS 11 – 252

Two-Impulse Rendezvous Near Circular Orbit Determined Through a New Primer Vector Analysis

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

This is the second of three papers on optimal impulsive rendezvous of a spacecraft in an inertial frame near a circular orbit. This study is restricted to non-degenerate two-impulse and one-impulse solutions.

Optimal non-degenerate nonsingular two-impulse rendezvous is found to consist of four categories of solutions depending on the four ways the primer vector locus intersects the unit circle. Necessary and sufficient conditions for each category of solutions are presented. The region of the boundary values that admit each category of solutions are found, and in each case a closed-form solution of the optimal velocity increments is presented. Some examples are simulated. Similar results are presented for the simpler optimal rendezvous that require only one-impulse. [View Full Paper]

SESSION 21: SPACE DEBRIS REMOVAL

Chair: Dr. Thomas Starchville, The Aerospace Corporation

AAS 11 – 253

A Preliminary Systems-Level Analysis of Candidate Active Space Debris Removal Architectures

Jesse R. Quinlan, Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology & National Institute of Aerospace, Hampton, Virginia, U.S.A.

To prevent a future cascading of space debris collisions in low-Earth-orbit (LEO), a multi-tiered approach to space debris remediation is necessary. Active debris removal (ADR) of massive debris is necessary, in addition to current mitigation guidelines, to delay the onset of collisional cascading. This study compares the effectiveness of proposed ADR concepts at a systems-level by first outlining a baseline ADR mission to LEO based on results from recent debris environment sensitivity studies in conjunction with tracking data for large debris. The author develops an independent set of figures of merit and subsequently uses the Analytic Hierarchy Process to compare the effectiveness of candidate ADR concepts against the baseline mission. [View Full Paper]

AAS 11 – 254

Active Debris Removal – A Grand Engineering Challenge for the Twenty-First Century

J.-C. Liou, NASA Orbital Debris Program Office, NASA Johnson Space Center, Houston, Texas, U.S.A.

The collision between Iridium 33 and Cosmos 2251 in 2009 has reignited interest in using active debris removal to remediate the near-Earth orbital debris environment. A recent NASA study shows that, in order to stabilize the environment in the low Earth orbit (LEO) region for the next 200 years, active debris removal of about five large and massive (1 to more than 8 metric tons) objects per year is needed. To develop the capability to remove five of those objects per year in a cost-effective manner truly represents a grand challenge in engineering and technology development. [View Full Paper]

AAS 11 – 255
(Paper Withdrawn)

AAS 11 – 256

Sling Satellite for Debris Removal With Aggie Sweeper

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

Low Earth Orbit is over cluttered by rogue objects. Traditional satellite missions are not efficient enough to collect an appreciable amount of debris due to the high cost of orbit transfers. Many alternate proposals are politically controversial, costly, or dependant on further technological advances. This paper proposes an efficient mission structure, “Aggie Sweeper,” and bespoke hardware, “Sling-Sat,” to de-orbit debris by capturing and appropriately expelling them. Momentum exchanges from these plastic collisions can assist orbit transfers to subsequent debris without burning fuel! Optimizing the collection sequence and method of interaction is a primary focus of this research. The proposed hardware also exploits existing momentum to save fuel. Capturing debris at the ends of a spinning satellite, adjusting angular rate, and then simply letting go at a specified time provides a simple mechanism for redirecting the debris.
[View Full Paper]

SESSION 22: ATTITUDE SENSOR
Chair: Al Treder

AAS 11 – 257
(Paper Withdrawn)

AAS 11 – 258
Geometrical Configuration Analysis of Redundant Inertial Measurement Units

Hector D. Escobar-Alvarez and **Maruthi R. Akella**, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas, Austin, Texas, U.S.A.; **Robert H. Bishop**, Dean of Engineering, Marquette University, Milwaukee, Wisconsin, U.S.A.

Inertial measurement units (IMUs) are used in a wide range of applications to estimate position, velocity, and attitude of vehicles. The high cost of tactical grade IMUs makes low-cost microelectromechanical systems (MEMS) based IMUs appealing. These MEMS type IMUs are less accurate, so to counteract this effect, multiple and different configurations should be used. The work presented here provides efficient and low cost solutions using different configurations of redundant (multiple) MEMS-IMU swarms, which increase the level of accuracy to potentially the order of that of a tactical IMU. Several geometric configurations are presented and their performance is quantitatively compared through different methods. [View Full Paper]

AAS 11 – 259
(Paper Withdrawn)

AAS 11 – 260

Star Tracker Real-Time Hardware in the Loop Testing Using Optical Star Simulator

Malak A. Samaan, **Stephen R. Steffes** and **Stephan Theil**, Navigation and Control Systems Department, DLR German Aerospace Center, Institute of Space Systems, Bremen, Germany

The demand for highly accurate attitude determination sensors has increased in the last few decades. One of the best and more accurate attitude determination sensors for spacecraft is the star tracker, which determines 3-axis attitude with an accuracy of a few arc-secs. In order to achieve this high accuracy, the star tracker hardware and software can be tested on-ground with an accurate optical simulator.

This work presents an open-loop and closed-loop hardware test bench to demonstrate a star tracker's functionality. The test bench consists of an optical star field simulator, a real-time simulation computer and the star tracker to be tested. A dSPACE real-time simulator is used to simulate vehicle attitude and the associated sky image is provided as input to the star tracker camera using the optical simulator. To close the simulation loop, the dSPACE simulator can respond to the star tracker measurements by changing the vehicle dynamics and thus the simulated star field image.

The hardware-in-the-loop test bench was used to test the star tracker for the Hybrid Navigation Experiment for the SHEFEX-2 sounding rocket mission, which will be launched in late 2011. The test bench was first calibrated and aligned to remove errors in the simulation. End-to-end results using both the open- and the closed-loop test benches are then analyzed and discussed, which include measuring the total turn-around time and maximum vehicle rotation rate for the star tracker. [View Full Paper]

AAS 11 – 261

Uniform Distribution of Points on a Sphere With Application in Aerospace Engineering

Daniele Mortari, Department of Aerospace Engineering, Texas A&M University, College Station, Texas, U.S.A.; **Martín Avendaño**, Visiting Assistant Professor, Math Department, Texas A&M University, College Station, Texas, U.S.A.; **Pedro Davalos**, Space Engineering Research Center, Texas Engineering Experiment Station, Texas A&M University, College Station, Texas, U.S.A.

This work describes two distinct approaches to build uniform star catalogs. This is done by developing two distinct algorithms to distribute N points on a sphere, problem known as the seventh Smale's problem. The first algorithm provides quasi-uniform points by splitting Platonic solids into subsequent spherical triangles of identical areas. This method can be applied for discrete values of $N = F\, 2^s$, where F is the number of triangles of the Platonic solid considered and s the number of divisions. The second approach works any value of N, by slicing the unit-sphere into a limited number depending on the decomposition of N into prime factors. The uniform star catalog is then built using two algorithms distributing the catalog stars into the quasi-uniform equal area bins. [View Full Paper]

SESSION 23: TRAJECTORY AND MISSION ANALYSIS
Chair: Dr. Sergei Tanygin, Analytical Graphics, Inc.

AAS 11 – 262
Analytical and Numerical Solutions for Error Transfer Matrix in Precision Transfer Trajectory Design and Midcourse Correction

Zhong-Sheng Wang, Department of Engineering Sciences, Embry-Riddle Aeronautical University, Daytona Beach, Florida, U.S.A.

The computation of error transfer matrix is critical in precision transfer trajectory design and mid-course correction for lunar or Mars missions. This paper discusses an analytical solution and a numerical solution in detail, and shows that using the numerical method is advantageous since it has great flexibility and allows the use of high precision dynamic model in the design process so that the end error in realistic simulations can be made negligible. This paper also redefines the end condition requirements and a two-step procedure for precision transfer trajectory design is proposed.
[View Full Paper]

AAS 11 – 263
GPU Accelerated Lambert Solution Methods for the Orbital Targeting Problem

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

Lamberts problem is concerned with the determination of an orbit that connects two position vectors within a specified time of flight. It must often be solved millions of times, especially when one is conducting global searches for possible gravity assist missions, which requires fast efficient solutions. The orbital targeting problem lends itself well to parallel processing, with each departure and arrival combinations being computationally separate. By using the parallel capabilities of modern Graphics Processing Unit (GPU) technology, it is possible to reduce the total run time of the search program by several orders of magnitude. Three methods, have been implemented on a GPU, with run times up to 1100 times faster, when compared to comparable serial FORTRAN verions, at a maximum of almost 20 million solutions per second. Two example missions, one to asteroid 99942 Apophis and a 200-year Earth to Mars search, have been conducted to evaluate the performance of each method. [View Full Paper]

AAS 11 – 264

Natural Loose Formation Flying Around Halo Orbits

Triwanto Simanjuntak, Department of Space and Astronautical Science, The Graduate University for Advanced Sciences (SOKENDAI), Sagamihara, Kanagawa, Japan; **Masaki Nakamiya** and **Yasuhiro Kawakatsu**, Department of Space Systems and Astronautics, Institute of Space and Astronautical Science (ISAS)/JAXA, Sagamihara, Kanagawa, Japan

Two spacecrafts are assumed to fly in a loose formation flying around a collinear lagrangian point of the Sun-Earth Circular Restricted Three-Body Problem (CRTBP) system. Orbit reference of choice for the leader is a halo orbit and the follower is conceived to follow nearby and constrained geometrically or in size. This type of formation could be useful in future for constructing space based ports, space telescopes, astronomical spacecrafts requiring sun shield, and with more constituents, spacecraft swarm missions. The formation design method is constructed by firstly sought the local coordinate system from the Monodromy matrix by extracting the independent directions which spanned the periodic subspace of the Halo orbit. We then approximate the relative motion of each direction by using Fourier series and linear function. Since the size of formation discussed here is significantly small compared with the size of the Halo orbit, we can devise formation design method simply as to how linearly combine the approximations. This consequently means that we transform the formation design problems into algebraic problems. Suppressing oscillation in the Sun-Earth direction is shown here among other things as an example to demonstrate the formation design method.
[View Full Paper]

AAS 11 – 265

Numerical Solutions to a New Type of Orbital Boundary-Value Problem With Specified Flight-Path Angle

Jian Li and **Chao Han**, School of Astronautics, Beihang University, Beihang University, Beijing, China

A new type of orbit boundary-value problem is investigated in this paper. Being different from the classical Lambert's problem, the new problem has a given flight-path angle and the time of flight or the range angle is not fixed. Analysis shows that if flight-path angle and time of flight are fixed, to ensure the existence of solutions, the range angle must be bounded and its corresponding boundary values are obtained. A procedure to solve the time of flight equation is developed based on the numerical exploration of its variation pattern. The results of numerical experiments suggested that there may be at most four solutions to a given problem. [View Full Paper]

AAS 11 – 266

Optimized GPU Simulation of a Disrupted Near-Earth Object Including Self Gravity

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

This paper focuses on the development of a simulation model for disrupting a Near-Earth Object (NEO) on terminal approach with the Earth. The problem is simulated numerically using a Graphics Processing Unit (GPU) architecture, and is designed to highlight the benefits of this technology. A high-fidelity model, including mutual gravitation and collisions between NEO fragments, is developed and tested for the GPU. The unique limitations of this computational infrastructure are presented, as well as optimization strategies applied to the present model. The results of this project reflect a new range of high-performance computing options available to the planetary defense research community. [View Full Paper]

AAS 11 – 267

Parameter Variation in Near-Earth Object Disruption Simulations Using GPU Acceleration

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

This paper focuses on the problem of disrupting a Near-Earth Object (NEO) on terminal approach with the Earth, investigating the effects of changing explosive power and timing the fragmentation to coincide with orbital dispersion properties. Simulation and analysis of previous results have shown that fragmenting and dispersing a hazardous NEO could lower the total mass impacting the Earth for some orbits. The problem is simulated numerically using the computational capabilities of a Graphics Processing Unit (GPU) to accelerate calculations and enable variation of several mission and orbital parameters. Model upgrades and higher resolution simulation capabilities are demonstrated for an Apophis-like orbit. Unique benefits and limitations to the GPU architecture are discussed, and preliminary results equivalent to months of serial computation are presented. [View Full Paper]

AAS 11 – 268

(Paper Withdrawn)

AAS 11 – 269

Trajectory Analysis of Spacecraft Propelled by Photonic Laser Propulsion System

T. H. Wang, **C. C. Lee**, **P. J. Yang**, **H. J. Wei**, **B. Y. Tsai** and **F. Y. Hsiao**,
Department of Aerospace Engineering, Tamkang University, Tamsui, Taiwan, R.O.C.

This paper studies the application of photonic laser propulsion (PLP) system to the trajectory analysis in a space mission. The PLP system is an innovative technology proposed by Dr. Bae. With repeated reflections of laser beam, it can generate continuous and tremendous power by consuming very small energy. When applying to the trajectory analysis in space flight, we model the problem as a circular restricted three-body problem, and the corresponded Jacobi integral is found. A contour of zero-velocity lines is presented. Equilibrium points under this system are also discussed and found. Numerical simulations are presented to show the validity of our derivations. The results obtained in this paper are directly applicable to the usage of the PLP thrust in the future, and potentially helpful to various space missions, including interplanetary traveling.
[View Full Paper]

SESSION 24: ATTITUDE DYNAMICS AND CONTROL II
Chair: Dr. Zhiqiang Zhou, NASA Langley Research Center

AAS 11 – 113

Operational Considerations for Attitude Control of the RBSP Spacecraft

Robin M. Vaughan and **Timothy G. McGee**, Space Department, The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, U.S.A.

The Radiation Belt Storm Probes (RBSP) mission plans to launch two Earth-orbiting spacecraft in 2012. The two spacecraft are major-axis spinners with no on-board attitude determination or control. The rotational dynamics are complicated by the interaction of the spacecraft bus with multiple appendages that include two pairs of long wire booms, one pair of shorter axial booms, four solar panels, and two magnetometer booms attached to the solar panels. This paper describes the design of spacecraft attitude maneuvers to satisfy engineering constraints and optimize science data return. The spacecraft are nearly Sun-pointed with allowable attitude for valid science data collection defined by limits on spin axis offset angles from the Sun line in and normal to the ecliptic plane. Further limits are placed on these offset angles to accommodate uncertainties in attitude knowledge and maneuver targeting control. Analyses of different aspects of the attitude constraints are combined to determine the best choice of nominal Sun offset angles and attitude maneuver frequency for the science phase of mission operations. While the maneuvers are needed to maintain the desired attitude, they also interrupt science data collection for some of the instruments. Strategies are presented to minimize the interruption time by selecting thruster pulse durations and time needed to settle dynamic perturbations after thruster pulsing is terminated. [View Full Paper]

AAS 11 – 270

Design of the Satellite Attitude Control System Using Multi-Objective Generalized Extremal Optimization

Igor Mainenti Lopes, **Luiz C G de Souza** and **Fabiano L. DeSouza**, National Institute for Space Research, São José dos Campos – SP – Brazil

In this work a new multi-objective optimization algorithm is presented. The main motivation to develop this new evolutionary algorithm, called M-GEO$_{real}$, is to improve the performance and robustness of the M-GEO algorithm previously developed and available in the literature. As a brand new algorithm, several tests have been performed previously with well-known test functions commonly used to verify the performance and robustness of optimization algorithm. In this work the performance and robustness of the M-GEO$_{real}$ algorithm is investigated in a practical problem, which consist in designing a non-linear control law to control a rigid-flexible satellite attitude. The multi-objective control law requirements are to minimize, simultaneously, the time and the energy during the satellite attitude maneuver. A great advantage of this multi-objective approach is to deal with a set of optimised trade-off creating a region of solutions (non-dominated) available to the designer for posterior choice of an individual solution to be implemented. The non-dominated solutions are represented in the design space (Pareto optimal set) and in the objective functions space (Pareto front). From this design space one gets the best non-linear control law gains to satisfy the performance and robustness requirements of the satellite attitude control system. It is also important to stress that the besides the M-GEO$_{rea}$l be an optimization algorithm it is able to deal with non-linear system, designing a nonlinear control law. From the Pareto Front one obverses that M-GEO$_{real}$ results are superior to the others two techniques, since its non-control law spend less energy to the same maneuvers time. The better robustness of the M-GEO$_{real}$ is characterized by the fact that it is able to control a non-linear plant.
[View Full Paper]

AAS 11 – 271

Impact-Angle Control of Asteroid Interceptors/Penetrators

Matt Hawkins and **Bong Wie**, Asteroid Deflection Research Center, Iowa State University, Ames, Iowa, U.S.A.

Many of the possible asteroid threat mitigation techniques call for the use of nuclear explosives to effect disruption of near-Earth objects. Such techniques impart as much momentum to the dispersed particles as possible. Subsurface nuclear explosions are the most effective option, but need to place the nuclear device as far under the surface as possible to maximize the amount of energy coupled from the nuclear device to the body. A guidance technique involving statistical orbit determination is discussed, and added as an option to an existing simulator for terminal-phase guidance. The asteroid Apophis is used as an illustrative example to show that a variety of nuclear penetrator missions are possible. A guidance scheme to change a spacecraft's approach angle towards the end of the mission for a low relative velocity is analyzed. A model for a new scenario, a leading kinetic-impact spacecraft followed several seconds later by a spacecraft with the nuclear payload, is described. Simulation results show that this new scenario may be promising, and factors that warrant further research are identified. The guidance schemes analyzed in this paper contribute to a simulator program with many options for different asteroid missions. [View Full Paper]

AAS 11 – 272
(Paper Withdrawn)

AAS 11 – 273
(Paper Withdrawn)

AAS 11 – 274
(Paper Withdrawn)

AAS 11 – 275

The Exact Attitude of a Triaxial Free Rigid Body Revisited

A. Elipe, Grupo de Mecánica Espacial-IUMA & Centro Universitario de la Defensa, Universidad de Zaragoza, Spain; **J. I. Montijano**, **L. Rández** and **M. Calvo**, Dpt. Applied Mathematics-IUMA, Universidad de Zaragoza, Spain.

The aim of this paper is to give a new description of the exact solutions of an asymmetric rigid body that combines a simplified 3D vector form of the angular velocity with a quaternion form for the attitude matrix. The main advantage in using such a quaternion expression for the attitude is that is free from singularities and with four parameters in the unit sphere of R_4 permits us to perform linear transformations within the simple algebra of quaternions. Because of this, it is well suited for the numerical integration of forced motions, and can be used as a benchmark for numerical integrators based on splitting methods, as well to obtain numerical solutions of attitude problems in astrodynamics. [View Full Paper]

AAS 11 – 276

Underactuated Unidirectional Magnetic Detumbling of Small Satellites

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

The detumbling mode is critical for the success of many spacecraft missions. This paper shows that unidirectional magnetorquers can be used to detumble a spacecraft. Two unidirectional switching controllers were developed. The first is a unidirectional B-dot controller and the second is an on-off unidirectional B-dot controller. Simulations were performed to compare the unidirectional controllers with the conventional B-dot controller. A combined power consumption and rotational kinetic energy performance metric was used to show that conditions exist where the unidirectional controllers have performance advantages over their bidirectional counterparts. [View Full Paper]

SESSION 25: LUNAR TRAJECTORY DESIGN
Chair: Lisa Policastri, Applied Defense Solutions

AAS 11 – 277

A Survey of Ballistic Transfers to Low Lunar Orbit

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

A simple strategy is identified to generate ballistic transfers between the Earth and Moon, i.e., transfers that perform two maneuvers: a trans-lunar injection maneuver to depart the Earth and a Lunar Orbit Insertion maneuver to insert into orbit at the Moon. This strategy is used to survey the performance of numerous transfers between varying Earth parking orbits and varying low lunar target orbits. The transfers surveyed include short 3-6 day direct transfers, longer 3-4 month low-energy transfers, and variants that include Earth phasing orbits and/or lunar flybys. [View Full Paper]

AAS 11 – 278

A Survey of Ballistic Transfers to the Lunar Surface

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

In this study techniques are developed which allow an analysis of a range of different types of transfer trajectories from the Earth to the lunar surface. Trajectories ranging from those obtained using the invariant manifolds of unstable orbits to those derived from collision orbits are analyzed. These techniques allow the computation of trajectories encompassing low-energy trajectories as well as more direct transfers. The range of possible trajectory options is summarized, and a broad range of trajectories that exist as a result of the Sun's influence are computed and analyzed. The results are then classified by type, and trades between different measures of cost are discussed.
[View Full Paper]

AAS 11 – 279
(Paper Withdrawn)

AAS 11 – 280
An Onboard Targeting Algorithm for Lunar Missions

Phillippe Reed and **Evans Lyne**, Department of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville, Tennessee, U.S.A.; **Greg Dukeman**, Guidance, Navigation and Mission Analysis Branch, NASA Marshall Space Flight Center, Huntsville, Alabama, U.S.A.

A targeting algorithm for use onboard a spacecraft has been developed. The algorithm determines the appropriate propulsive burn for trans-lunar injection to obtain desired orbital parameters upon arrival at the moon. The primary design objective was to minimize the computational requirements for the algorithm but also to ensure reasonable accuracy, so that the algorithm's errors did not necessitate large mid-course corrections. The algorithm will serve as a viable alternative to uploading ground-based targeting solutions and bypass the problems of delays and disruptions in communication, enabling the craft to conduct a trans-lunar injection burn autonomously. [View Full Paper]

AAS 11 – 281
Characterization of Numerical Error in the Simulation of Translunar Trajectories using the Method of Nearby Problems

Ashish A. Jagat and **Andrew J. Sinclair**, Department of Aerospace Engineering, Auburn University, Auburn, Alabama, U.S.A.

This paper focuses on analyzing the effect numerical error has on the accurate simulation of translunar trajectories. The method of nearby problems is employed to estimate the numerical error. A simulation is developed to generate translunar trajectories. Analytical curve fit is generated to this numerical solution and this curve fit is used to compute source terms. The addition of these source terms to the governing equations defines a nearby problem, for which the curve fit serves as an exact solution. By solving the nearby problem numerically, the numerical error in the nearby problem can be calculated. This facilitates the characterization of numerical error in the original problem. [View Full Paper]

AAS 11 – 282
(Paper Withdrawn)

AAS 11 – 283

Ways to the Moon: A Survey

G. Mingotti, Institut für Industriemathematik, Universität Paderborn, Germany;
F. Topputo, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Italy

This paper summarizes some works done by the authors where a number of new ways to reach the Moon has been described. The scope is to assess these solutions for the sake of comparison with existing examples. This survey contains low- and high-energy transfers, obtained with both low- and high-thrust propulsion. Solutions considered ranges from classic low energy transfers, to transfers using distant periodic and halo orbits. A thorough comparison is made in terms of flight time, propellant mass fraction, total Δv, number of maneuvers, duration of thrust and coast arcs, and dynamical models. [View Full Paper]

DIRK BROUWER AWARD PLENARY LECTURE

AAS 11 – 284

In the Beginning There Were Comets and Asteroids – Now There is Earth-Orbiting Debris (Abstract and Biography Only)

Donald J. Kessler

Early in the space program models and data were developed to understand the hazard to spacecraft from small fragments originating from asteroids and comets; by 1970 it was concluded that the hazard was manageable. However, years later, when similar models and data were used to determine the possible hazard from spacecraft fragments in Earth orbit, a different conclusion was reached: The orbital-debris hazard could quickly become unmanageable. After a rocky beginning, the NASA Orbital Debris Program is now officially over 30 years old, international in scope, and is continuing to take on increasing responsibilities. This lecture will identify the technical and political misconceptions that delayed the recognition and acceptance of the program and will discuss current findings and the direction the program must take. It will illustrate that, where statistical models applied to a small amount of data were sufficient to identify the orbital debris problem, more sophisticated models will likely be required to solve the problem. [View Full Summary]

Author Index

Author	Session	Paper Number
Humi, Mayer	20 20	AAS 11-251 AAS 11-252
Hurtado, John E.	1	AAS 11-106
Jagat, Ashish A.	25	AAS 11-281
Jah, Moriba K.	14	AAS 11-201
Johnson, Andrew	16	AAS 11-221
Johnson, Kirk W.	15	AAS 11-214
Johnson, Shawn C.	24	AAS 11-276
Jones, Jeremy B.	16	AAS 11-216
Junkins, John L.	4 9	AAS 11-128 AAS 11-168
Kahle, Ralph	19	AAS 11-245
Kaplinger, Brian D.	23 23	AAS 11-266 AAS 11-267
Karimi, Reza Raymond	3	AAS 11-121
Karpenko, M.	2	AAS 11-110
Kasai, Toru	6	AAS 11-145
Kawaguchi, Jun'ichiro	18	AAS 11-235
Kawakatsu, Yasuhiro	23	AAS 11-264
Kéchichian, Jean A.	18	AAS 11-238
Kelso, T. S.	7	AAS 11-151
Kessler, Donald J.	Awards	AAS 11-284
Kharytonov, Oleksii	12	AAS 11-190
Kidd, John N., Jr.	1	AAS 11-100
Kiehling, Reinhard	19	AAS 11-245
Kim, D.	5	AAS 11-136
Kim, Hae-Dong	10	AAS 11-176
Kimura, Shinichi	19	AAS 11-246
Kirschner, Michael	19	AAS 11-245
Klesh, Andrew T.	19	AAS 11-246
Klimcak, Charles M.	13	AAS 11-196
Klinc, Milan	3	AAS 11-120
Kluever, Craig A.	18	AAS 11-233
Kocher, Yves	13	AAS 11-199

Author	Session	Paper Number
Kolmanovsky, Ilya V.	6 18	AAS 11-142 AAS 11-232
Konopliv, Alex S.	14	AAS 11-203
Kumar, Vishwajeet	7	AAS 11-148
Lafleur, Jarret M.	10	AAS 11-173
Landau, Damon	1	AAS 11-102
Lara, Martin	19	AAS 11-239
Latchman, Haniph	5	AAS 11-132
Lázaro, David	3	AAS 11-120
Lechtenberg, Travis F.	10	AAS 11-174
Lee, C. C.	23	AAS 11-269
Lee, Unsik	3	AAS 11-117
Leve, F. A.	5	AAS 11-136
Li, Jian	23	AAS 11-265
Liang, Ye	10	AAS 11-171
Linares, Richard	2 5 7 15	AAS 11-114 AAS 11-138 AAS 11-148 AAS 11-208
Liou, J.-C.	21	AAS 11-254
Liu, Shenggang	17	AAS 11-223
Lo, Martin W.	4 4 17	AAS 11-125 AAS 11-129 AAS 11-229
Locke, Travis	10	AAS 11-174
Long, Anne	14	AAS 11-207
Lopes, Igor Mainenti	24	AAS 11-270
Lovell, T. Alan	15 15	AAS 11-208 AAS 11-214
Lu, Wenwen	14	AAS 11-203
Luo, Qinqin	10	AAS 11-171
Lyne, Evans	25	AAS 11-280
Macdonald, Malcolm	18	AAS 11-236
Majji, Manoranjan	1 9	AAS 11-106 AAS 11-168
Mance, Stephen R.	10	AAS 11-174

Author	Session	Paper Number
Muñoz, Josue D.	2	AAS 11-111
	24	AAS 11-276
Nagabhushan, Vivek	2	AAS 11-111
	13	AAS 11-197
Nakamiya, Masaki	23	AAS 11-264
Newman, Brett	15	AAS 11-211
	15	AAS 11-212
	20	AAS 11-247
Nievinski, Felipe G.	3	AAS 11-119
Ning, Yu	5	AAS 11-133
	6	AAS 11-143
Nolet, Simon	16	AAS 11-216
Norman, Michael C.	9	AAS 11-164
Ober-Blöbaum, Sina	4	AAS 11-127
O'Connell, Dylan	16	AAS 11-218
Okasha, Mohamed	15	AAS 11-211
	15	AAS 11-212
Oleson, Steven R.	12	AAS 11-187
Olson, Corwin	14	AAS 11-207
Oltrogge, Daniel L.	7	AAS 11-151
Ortigosa, David	8	AAS 11-161
O’Shaughnessy, Daniel J.	9	AAS 11-164
Owen, William M., Jr.	16	AAS 11-215
	16	AAS 11-217
	16	AAS 11-218
	16	AAS 11-221
	16	AAS 11-222
Parcher, Daniel W.	11	AAS 11-180
	11	AAS 11-183
	11	AAS 11-186
Park, Hyeongjun	6	AAS 11-142
Park, Ryan S.	14	AAS 11-203
Parker, Jeffrey S.	25	AAS 11-277
	25	AAS 11-278
Parsley, Joseph	9	AAS 11-166
Patankar, Kunal	9	AAS 11-170
Peck, Mason A.	9	AAS 11-164
Pernicka, Henry J.	6	AAS 11-139

Author	Session	Paper Number
Schmidt, Uwe	13	AAS 11-198
Schutz, Bob E.	3	AAS 11-118
Scott, Christopher	12	AAS 11-188
Seago, John H.	3	AAS 11-123
	7	AAS 11-151
Selnick, Scott	9	AAS 11-167
Sharma, Rajnish	9	AAS 11-166
Sherrill, Ryan E.	15	AAS 11-208
	15	AAS 11-214
Shishido, John	13	AAS 11-195
Short, Cody R.	20	AAS 11-250
Simanjuntak, Triwanto	23	AAS 11-264
Sinclair, Andrew J.	15	AAS 11-208
	15	AAS 11-214
	25	AAS 11-281
Singla, Puneet	7	AAS 11-148
Smith, Craig	14	AAS 11-205
Song, Young-Joo	10	AAS 11-176
Speyer, Jason	18	AAS 11-234
Starek, Joseph A.	18	AAS 11-232
Steffes, Stephen R.	22	AAS 11-260
Strange, Nathan	1	AAS 11-102
Subbarao, Kamesh	7	AAS 11-149
Suzuki, Masaharu	6	AAS 11-145
Synnott, Stephen P.	16	AAS 11-217
Tanaka, Keita	18	AAS 11-235
Tang, Zhongxing	17	AAS 11-228
Tanygin, Sergei	5	AAS 11-134
	5	AAS 11-137
Tardivel, Simon	11	AAS 11-179
Tarzi, Zahi	18	AAS 11-234
Theil, Stephan	22	AAS 11-260
Topputo, F.	25	AAS 11-283
Tricoche, Xavier M.	20	AAS 11-250
Tsai, B. Y.	23	AAS 11-269

Author	Session	Paper Number
Yonko, Brandon	3	AAS 11-119
Yoon, Sungpil	3	AAS 11-118
Yoshikawa, Shoji	6	AAS 11-145
Younes, Ahmad Bani	9	AAS 11-168
Zeiler, Tom	4	AAS 11-124
Zhang, Kefei	14	AAS 11-205
Zhao, Xiaofang	17	AAS 11-223
Zimmerman, Dan	1	AAS 11-103