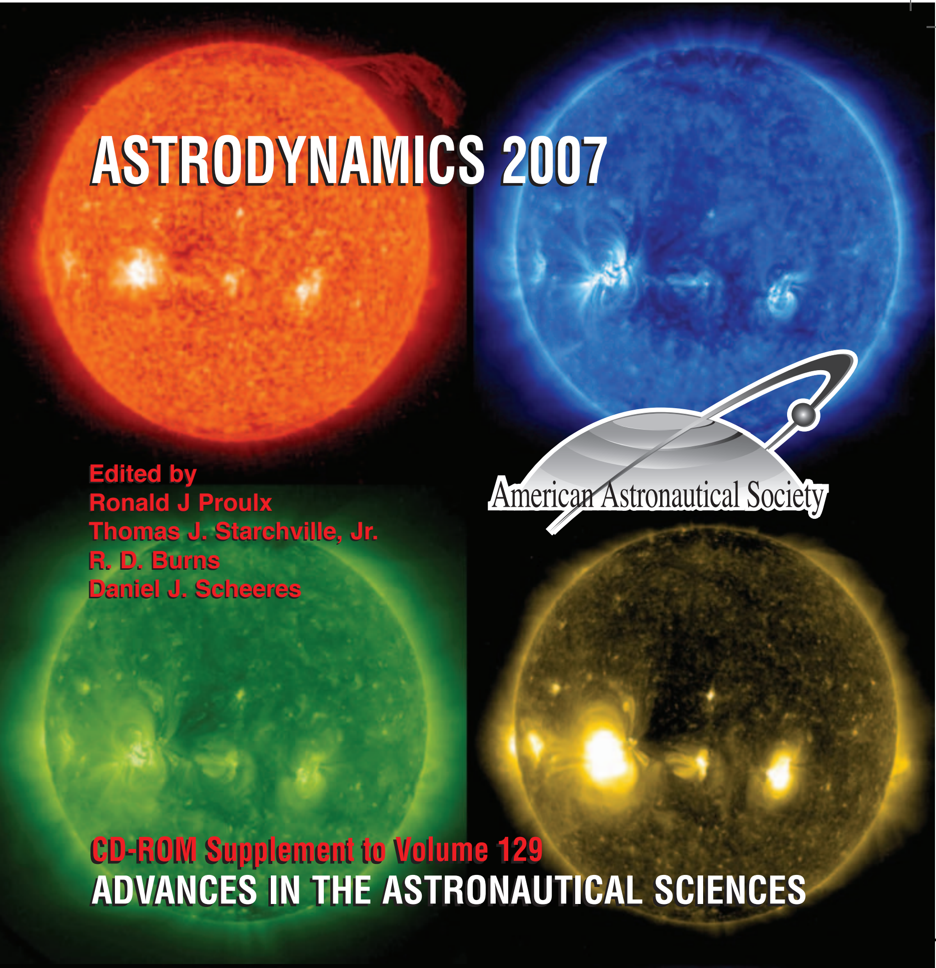

ASTRODYNAMICS 2007

Edited by
Ronald J Proulx
Thomas J. Starchville, Jr.
R. D. Burns
Daniel J. Scheeres

American Astronautical Society

CD-ROM Supplement to Volume 129
ADVANCES IN THE ASTRONAUTICAL SCIENCES

ASTRODYNAMICS 2007

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Images from the STEREO Satellites – June Days (Photo Credit: Jet Propulsion Laboratory).

ASTRODYNAMICS 2007

Volume 129

ADVANCES IN THE ASTRONAUTICAL SCIENCES

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Proceedings of the AAS/AIAA Astrodynamics Specialist Conference held August 19-23 2007, Mackinac Island, Michigan.

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 2008

Library of Congress Card No. 57-43769

ISSN 0065-3438

ISBN 978-0-87703-543-5 (Hard Cover Plus CD ROM)

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.

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FOREWORD

The 2007 Astrodynamics Conference was hosted by the American Astronautical Society (AAS) and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA). The conference was held August 19-23, 2007, Mackinac Island, Michigan. There were some 150 papers presented in 24 technical sessions. Session topics included Cassini, atmospheric density analysis, satellite constellations and formation flying, trajectory design and planetary mission studies, orbit determination and tracking, attitude dynamics, determination and control, atmospheric re-entry guidance and control, spacecraft guidance, navigation and control, 50 years of space development, low thrust mission and trajectory design, dynamics and control of large space structures, STEREO, trajectory optimization, space debris and conjunction analysis, orbital dynamics, perturbations and stability and earth orbital and planetary mission studies.

These astrodynamics conferences have been held annually since the mid-1960s, managed alternately by the American Astronautical Society and the American Institute of Aeronautics and Astronautics. Every second year the American Astronautical Society publishes the proceedings. The proceedings usually consist of a hard-copy volume or set of volumes plus a microfiche or CD ROM supplement. This volume, *Astrodynamics 2007*, Volume 129, *Advances in the Astronautical Sciences*, consists of three parts totaling about 3000 pages, plus a CD ROM supplement which includes the papers in digital form. All of the available papers appear in full in Volume 129. A chronological index and an author index are appended to the third part of the volume. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume.

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

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

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

The current proceedings are valuable in keeping 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.

AAS/AIAA ASTRODYNAMICS VOLUMES

Astrodynamics 2007 appears as Volume 129, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Astrodynamics Conference 2007.

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.

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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*)

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

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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*).

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

American Astronautical Society (AAS) http://www.space-flight.org/ and http://www.astronautical.org/

American Institute for Aeronautics and Astronautics (AIAA) http://www.aiaa.org/

PREFACE

The 2007 AAS/AIAA Astrodynamics Specialists Conference was held from August 19 through August 23, 2008, on Mackinac Island, Michigan at the Mission Point Resort. The conference was co-sponsored by the American Astronautical Society (AAS) and the American Institute of Aeronautics and Astronautics (AIAA), and organized by the AAS Space Flight Mechanics Technical Committee and the AIAA Astrodynamics Technical Committee. There were over 190 registered participants, with including engineers, scientists and mathematicians from around the world, representing industry, academia and government agencies.

There were 156 technical papers presented in 24 sessions covering a large spectrum of Astrodynamics topics, including the design and control of satellite constellations; trajectory design and trajectory optimization, planetary mission studies; satellite attitude dynamics, determination and control; satellite orbit determination; and the dynamics and control of large structures; space debris; and spacecraft guidance, navigation and control. There were special sessions on two space science missions: STEREO, organized by Jose Guzman and Cassini, organized by Fred Pelletier and Peter Antresian.

There were two events to commemorate the fifty years of space flight. The first was a a very well received and attended special technical session, organized and co-chaired by Dr. Thomas Eller and Dr. Tony Hagar, on the 50 years of Space Development since Sputnik was launched. The second event was a plenary lecture by Dr. Roger Launius, who is from the Division of Space History, the Smithsonian Institution National Air and Space Museum. He gave an inspiring lecture entitled “Space: Journeying Toward the Future,” which provided a survey of space flight history together with comments on the major challenges we will see in spaceflight during the 21st century. His appearance was supported by the AIAA Distinguished Lecturer Series.

At this event, a special award was provided to Dr. Kathleen Howell by Mark Craig, president of the American Astronautical Society, for her years of service to the society as editor-in-chief of the *Journal of Astronautical Sciences*, the AAS peer-reviewed technical journal.

A special course on trajectory optimization entitled “Emerging principles in Fast Trajectory Optimization” was held on Sunday, August 19. Presented by I. M. Ross, Naval Postgraduate School, and Q. Gong, University of Texas at San Antonio, the course explored several advances that have taken place over the last decade in both the theory and computation methods of optimal control and trajectory optimization.

The editors of these proceedings would like to extend their appreciation to all the authors, as these proceedings would not exist without them. A special thanks to the session chairs, and to Shannon Coffey for his continuing support of the Abstract Administration Website.

We would like to also express our thanks The Charles Stark Draper Laboratory for supporting the cost of printing the conference program. The program cover was designed by Tomas Starchville, the AIAA Technical Chair, of the Aerospace Corporation.

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NASA GoddardSpaceflight Center

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The Charles Stark Draper Laboratory

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SESSION 1: SPECIAL SESSION - CASSINI
Chair: Mr. Peter Antreasian, Jet Propulsion Laboratory

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Optical Navigation for the Cassini/Huygens Mission

S. D. Gillam, W. M. Owen Jr., A. T. Vaughan, T.-C. M. Wang, J. D. Costello, R. A. Jacobson, D. Bluhm, J. L. Pojman and R. Ionasescu, Jet Propulsion Laboratory

Navigation of the Cassini orbiter and release of the Huygens probe to Saturn's moon Titan depended partly on high quality ground optical navigation data processing. 2200 pictures of Saturn's nine major satellites and occasional calibration fields were taken with the Cassini narrow angle camera (NAC). These provide the position of the spacecraft in two dimensions relative to the satellites. These measurements are used to improve estimates of the orbital elements of the satellites and the position of the spacecraft. This paper describes the satellite center finding tools and the opnav results that contribute to the continuing success of the mission.

AAS 07 – 253
Cassini Orbit Determination Performance During Saturn Satellite Tour: August 2005 – January 2006

P. G. Antreasian, J. J. Bordi, K. E. Criddle, R. Ionasescu, R. A. Jacobson, J. B. Jones, R. A. MacKenzie, D. W. Parcher, F. J. Pelletier, D. C. Roth and J. R. Stauch, Jet Propulsion Laboratory

During the period spanning the second Enceladus flyby in July 2005 through the eleventh Titan encounter in January 2006, the Cassini spacecraft was successfully navigated through eight close-targeted satellite encounters. Three of these included the 500 km flybys of the icy satellites, Hyperion, Dione and Rhea and five targeted flybys of Saturn's largest moon, Titan. This paper will show how our refinements to Saturn's satellite ephemerides have improved orbit determination predictions. These refinements include the mass estimates of Saturn and its satellites to better than 0.5%. Also, it will be shown how this better orbit determination performance has helped to eliminate several statistical maneuvers that were scheduled to clean-up orbit determination and/or maneuver-execution errors.

AAS 07 – 254

Cassini-Huygens Maneuver Experience: Third Year of Saturn Tour

Powtawche N. Williams, Emily M. Gist, Troy D. Goodson, Yungsun Hahn, Paul W. Stumpf and Sean V. Wagner, Jet Propulsion Laboratory

The Cassini-Huygens spacecraft was launched in 1997 on a mission to observe Saturn and its many moons. After a seven-year cruise, Cassini-Huygens entered the Saturn orbit in 2004 for a four-year mission. This paper highlights significant maneuver activities performed during the third year of the tour. Specifically, results of 54 maneuvers, orbit trim maneuvers 65 to 118, are presented. Successful execution of these maneuvers have enabled Cassini-Huygens to complete the closest Titan flybys in the tour, as well as achieve inclined orbit geometries to obtain never-before-seen views of Saturn and its rings.

AAS 07 – 255

Re-Aiming Cassini's Iapetus Flyby

Frederic Pelletier, Brent B. Buffington, Nathan Strange, Jet Propulsion Laboratory; Tilmann Denk, Freie Universität, Berlin, Germany

Cassini's only targeted Iapetus flyby is scheduled for September 10, 2007. In 2006, inquiries were made to investigate the possibility to improve the flyby geometry. After numerous discussions and design variations, modifications to the trajectory were adopted by the project in early 2007. The goal of the designers was to achieve a flyby geometry that maximizes the science results for a reasonable additional propellant cost. This involved (as a major driver) the reassessment of a star occultation that took away observation time from remote sensing of the surface . Ground-tracks were also studied to ensure the observation of very interesting features near the satellite's equatorial line.

AAS 07 – 256

500-Year Eccentric Orbits for the Cassini Spacecraft within the Saturn System

Chris Patterson, Masaki Kakoi, Kathleen C. Howell, Chit Hong Yam and James M. Longuski, Purdue University

One option for efficient and safe disposal of the Cassini spacecraft will be decided at some point prior to the end of the mission. Eccentric, long-term orbits between the Saturnian moons may offer continued observations for an extended period of time. Orbit design strategies to prevent collisions with any moons, particularly Titan, are a significant challenge, however. An eccentric orbit about Saturn with periapsis above Titan can be achieved such that the orbit is maintained under all relevant gravitational perturbations for 500 years or more. Insertion into such an orbit is accomplished via Titan encounters and with limited delta-V capability.

AAS 07 – 257

Saturn Impact Trajectories for Cassini End-of-Life

Chit Hong Yam, Diane Craig Davis, James M. Longuski and Kathleen C. Howell, Purdue University

We design Saturn impact trajectories for the end-of-life of the Cassini spacecraft. For short-period orbits (6-10 days), we use a Tisserand graph to determine when the ring-plane crossing distance is within the ring-gap to reencounter Titan. To impact Saturn with short-period orbits, the spacecraft hops through the rings of Saturn via successive Titan flybys to place the periapsis in Saturn's atmosphere. For long-period orbits (550-900 days), solar gravity plus a small apoapse maneuver can lower the spacecraft's periapsis to impact Saturn. For certain orbits with periods > 900 days, no maneuver is necessary, providing an attractive "flyby-and-forget" option.

AAS 07 – 258

Cassini End-of-Life Escape Trajectories to the Outer Planets

Masataka Okutsu, Chit Hong Yam and James M. Longuski - Purdue University;
Nathan J. Strange, Jet Propulsion Laboratory

We investigate escape trajectories via gravity assist from Titan as an option for a contamination-free, end-of-life scenario for the Cassini spacecraft. The Saturn-escape energy will be large enough to reach anywhere from the asteroid belt to the Kuiper belt, including the orbital radii of all gas giants, from Jupiter (at 5 AU) to Neptune (at 30 AU). In one example, we present a transfer to Jupiter in which the Cassini spacecraft escapes Saturn in 2013 to impact Jupiter nine years later.

SESSION 2: ATMOSPHERIC DENSITY ANALYSIS
Chair: Mr. John Seago, Analytical Graphics, Inc.

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Determination of Drag Coefficient Values for CHAMP and GRACE Satellites using Orbit Drag Analysis

Bruce R. Bowman, Air Force Space Command; Frank A. Marcos, Air Force Research Laboratory; Kenneth Moe and Mildred M. Moe, Space Environment Technologies

The CHAMP and GRACE satellites provide the opportunity to analyze very fine density structures within the thermosphere. However, previous efforts to calibrate the accelerometer data among the different satellites and with density drag data have shown large biases among the different data sets. These large biases in the accelerometer densities are a result of using drag coefficients that are too small for these long stabilized satellites at 400 to 500 km altitude. Using the HASDM atmospheric density corrections in the orbit determinations of the CHAMP and GRACE satellites results in an observed drag coefficient of 3.3 to 3.4 for both satellites. Theoretical drag coefficients are shown to be in agreement with the HASDM observed drag coefficient values.

AAS 07 – 260

Neutral Density Determined from CHAMP Precision Orbits

Craig A. McLaughlin, University of Kansas; Ben S. Bieber, University of North Dakota

Atmospheric density modeling has long been one of the greatest uncertainties in the dynamics of low Earth satellite orbits. Accurate density calculations are required to provide meaningful estimates of the atmospheric drag perturbing satellite motion. This paper uses precision satellite orbits from the Challenging Minisatellite Payload (CHAMP) satellite to produce a new data source for upper atmospheric density and changes that occur on time scales less than a day. The precision orbit derived density is compared to CHAMP accelerometer derived density to determine the accuracy of using precision orbit derived density.

AAS 07 – 261

Standardized Approaches for Estimating Orbit Lifetime after End-of-Life

Daniel L. Oltrogge, 1Earth Research, LLC;
Chia-Chun (George) Chao, The Aerospace Corporation

This paper details the development of analytical approaches and procedures to reasonably determine orbit lifetimes for post-mission orbits, accounting for nonlinearities of solar and geomagnetic indices, solar cycle phasing, drag coefficient variations, orbit-to-Sun geometry variations, and the recently-observed thermospheric cooling effect. These techniques were developed to support the development of a draft standard for the International Standards Organization (ISO) to help reduce long-term collision risk in the LEO orbit regime by ensuring that the pre-launch assessment of orbital lifetime is done carefully and accurately, using standardized analysis methods.

AAS 07 – 262

Drag Coefficient Variability at 100-300 km from the Orbit Decay Analyses of Rocket Bodies

Bruce R. Bowman and Stan Hrncir, Air Force Space Command

In the past it has been customary to always use the drag coefficient 2.2 for satellites of compact shapes when calculating atmospheric densities. This constant value is not applicable for use in computing decays as the satellite descends down to 100 km heights. In this analysis drag coefficient variability for different shaped rocket bodies is determined as a function of satellite altitude. A density determination method using HASDM atmospheric density corrections was used to compute drag coefficients from the orbit decay of numerous types of upper stage rocket bodies.

AAS 07-263
Withdrawn

AAS 07 – 264

Orbit Decay Prediction Sensitivity to Solar Flux Variations

Bo J. Naasz and Kevin Berry, NASA Goddard Spaceflight Center;
Kenneth Schatten, ai Solutions, Inc.

It is well known that atmospheric density errors are the main source of uncertainty in orbit decay predictions. Perhaps less well known is the sensitivity of atmospheric density to solar activity. In this paper, we examine the sensitivity of orbit decay predictions to realistic daily variations in solar flux. We present results from analysis of orbit decay prediction for a variety of orbits, initial epochs, and predicted smooth flux profiles. For each set of initial conditions, we simulate 1000 sample flux profiles with simulated daily variations, and compute the orbital reentry date for comparison.

AAS 07 – 265

Preliminary Results from the Atmospheric Neutral Density Experiment Risk Reduction Mission

A. C. Nicholas, J. M. Picone, J. Emmert, J. DeYoung, L. Healy and L. Wasiczko, Naval Research Laboratory; M. Davis, Honeywell TSI;
C. Cox, Raytheon Integrated Defense Systems

The Atmospheric Neutral Density Experiment (ANDE) Risk Reduction flight was launched on Dec 9, 2006 and deployed into orbit by the Space Shuttle Discovery on December 21, 2006. The primary mission objective is to test the deployment mechanism from the Shuttle for the ANDE flight in mid 2009. Atmospheric densities derived from observations of the ANDERR spacecraft will be presented and compared to atmospheric models and other data sources. A methodology to improve prediction accuracy by augmenting predictions produced with radar observations with combination radar and satellite laser ranging observations will be presented.

SESSION 3: SATELLITE CONSTELLATIONS AND FORMATION FLYING - I
Chair: Dr. Alan Segerman, AT&T

AAS 07-266
Withdrawn

AAS 07 – 267

1-D Constrained Coulomb Structure Stabilization With Charge Saturation

Shuquan Wang and Hanspeter Schaub, University of Colorado at Boulder

A Coulomb structure is a cluster of satellites which maintains its shape through inter-vehicle electrostatic forces. This paper investigates the 1-D restricted motion of a 3-craft cluster. Two charge feedback strategies are discussed where the charge saturation limitation is considered. First a continuous feedback strategy is presented, and its stability in the presence of charge limits discussed. Next, a saturated control strategy is developed to arrest any relative motion rates of the Coulomb structure. Implementable real-charge solutions are ensured through scaling the Lyapunov function rate. Because of the limitation of the control charges, some initial conditions will not lead to a zero formation expansion rate. Conditions under which the relative motion of the Coulomb structure can be stabilized are analyzed through investigating the total energy.

AAS 07 – 268

Analytic Solutions for Equal Mass 4-Craft Static Coulomb Formation

Harsch Vasavada and Hanspeter Schaub, Virginia Tech

This paper investigates analytic charge solutions for planar and 3D 4-craft static Coulomb satellite formations. The solutions are formulated in terms of the formation geometry and attitude. In contrast to the 2 and 3 spacecraft formations, a 4-craft formation has additional constraints that need to be satisfied for the individual spacecraft charges to be both unique and real. The nullspace of the planar 4-craft configuration is exploited to find individual spacecraft charges. Further, the 3-D tetrahedron formation scenario is also investigated. The implementability constraints are numerically evaluated sweeping across two Euler angles while holding the third constant.

AAS 07 – 269

Stability and Control of Relative Equilibria for the Three-Spacecraft Coulomb Tether Problem

Islam I. Hussein, Worcester Polytechnic Institute; Hanspeter Schaub, Virginia Tech

In this paper, we derive general conditions whose solutions are all relative equilibria for the spinning three-craft Coulomb tether constellation. In particular, we derive the collinear three-craft spinning family of solutions. We also derive stability conditions for the family of collinear solutions and show that no other solutions (e.g., triangular configurations) exist. We rely on the use of the energy-momentum method to determine stability.

AAS 07 – 270

Modeling and Properties of a Flux-Pinned Network of Satellites

Michael Norman and Mason A. Peck, Cornell University

Satellite formations typically have to rely upon active control methods to maintain stable configurations. This requirement imposes an associated cost on the satellite through fuel expenditure, actuator mass, and necessary computational power. This paper proposes utilizing the flux-pinning interaction between a superconductor and a magnetic field as a means to passively stabilize a satellite formation at equilibrium, reducing these costs. By modeling the flux-pinning effect as a set of linear equations, we can examine the stability of such a system. We apply this design to formation keeping and reconfiguration and demonstrate viability through analysis of a theoretical sparse-aperture telescope.

AAS 07 – 271

A General Methodology for Minimum-Fuel Hovering Satellite Formations

David J. Irvin Jr. and Richard G. Cobb, Air Force Institute of Technology;
T. Alan Lovell, Air Force Research Laboratory

A current problem of interest to mission planners is the ability of a deputy satellite to “hover” within a defined volume fixed in the vicinity of a chief satellite for an extended period of time. Recent research has developed methodologies for maintaining restricted tear drop hover orbits in a fixed plane within the chief’s frame. Additional papers have developed strategies for fuel-optimal trajectories restricted to chiefs in circular orbits and trajectories contained within the orbit plane. This research relaxes those assumptions to allow hovering about a chief in any orbit and in any specified volume in three space.

AAS 07 – 272

Withdrawn

AAS 07 – 273

Neighbouring Optimum Feedback Control Law for Earth-Orbiting Formation Flying Spacecraft

Jean-Francois Hamel and Jean de Lafontaine, Universite de Sherbrooke, Canada

This paper presents the development of a neighbouring optimum feedback control law for formation flying spacecraft. This controller is based on optimal control theory and performs a fuel/formation accuracy trade-off with the selection of only one gain. The controller is in the semi-analytic form, as only one time-varying gain matrix needs to be computed prior to the maneuver. It guarantees near-optimality for all the members of the formation. Simulation results compare the performance of this controller with other common formation flying control algorithms: the Linear Quadratic Regulator and the Mean Orbit Elements controller.

AAS 07 – 274

Time-Varying Expression of the Formation Flying Along Circular Trajectories

Jun'ichiro Kawaguchi and Ryu Funase, ISAS/JAXA, Japan

Usually, the formation flying associated with circular orbits is discussed through the well-known Hill's or C-W equations of motion. This paper dares to present and discuss the coordinates that may contain time-varying coefficients. The discussion presents how the controller's performance is affected by the selection of coordinates, and also looks at the special coordinate suitable for designating a target bin to which each spacecraft in the formation has only to be guided. It is revealed that the latter strategy may incorporate the J2 disturbance automatically.

SESSION 4: TRAJECTORY DESIGN AND PLANETARY MISSION STUDIES - I

Chair: Mr. Frederic Pelletier, Jet Propulsion Laboratory

AAS 07 – 275

Solar Gravity Perturbations to Facilitate Long-Term Orbits: Application to Cassini

Diane Craig Davis, Chris Patterson and Kathleen Howell, Purdue University

The Sun's gravitational acceleration is not often a focal point in the design of spacecraft trajectories about an outer planet, but the impact of solar gravity is potentially significant, especially on large orbits. Solar gravity is exploited in the design of trajectory options that support possible end-of-life scenarios for the Cassini spacecraft. Combining solar perturbations with Titan encounters and small maneuvers, the spacecraft can reach various long-term orbits, for example, quasi-circular Saturnian orbits beyond the radius of Phoebe. After a number of Saturn-centered revolutions, other trajectories depart the Saturnian system. A possible return to Saturn within 500 years is considered.

AAS 07 – 276

Patched-Integrated Gravity-Assist Trajectory Design

Brent Buffington and Nathan Strange, Jet Propulsion Laboratory

Patched conics have long been the means by which gravity-assist trajectories have been constructed for preliminary analysis. However, Keplerian orbits aren't always sufficient to design a tour that meets a mission's science requirements. For the design of the Cassini extended mission, perturbations by Saturn's oblate gravity field had to be accounted for in order to accurately design flybys of Saturn's small inner moons, and to better manage the delta-v expended in high-inclination orbits. In response, a method was developed to patch together central-body integrated trajectories with Keplerian orbits modeling gravity-assists. This method proved invaluable in the design the Cassini extended mission.

AAS 07 – 277

Mapping the V-Infinity Globe

Nathan Strange, Ryan Russell and Brent Buffington, Jet Propulsion Laboratory

Plotting a globe with all orbits sharing the same flyby V-Infinity provides a graphical method for the design and visualization of gravity-assist tours. This graphical method collapses a large and complex space of possible trajectories to a map on which a tour designer may use intuition and experience to design a gravity-assist tour. This method was used with great success in the Cassini extended mission design.

AAS 07 – 278

Withdrawn

AAS 07 – 279

Withdrawn

AAS 07 – 280

Optimal Trajectories for Soft Landing on Asteroids

Gregory Lantoine and Robert D. Braun, Georgia Institute of Technology

This paper describes a technique for computing optimal autonomous controlled trajectories for soft landing in an irregular gravity field of an asteroid. We will first discuss how we can model the complex forces that act on the spacecraft during a landing. Then, we will present the numerical method used to solve the optimal control problem, and typical results are shown on case studies at asteroids Vesta and Golevka. In each example, we will identify the best mission design scenarios and some operational difficulties. Finally, we will investigate sensitivity to parameter uncertainties and the implementation of a real-time feedback controller.

AAS 07 – 281

Comparison between Patched Conic and Perturbed Orbit for Mars Mission

B. P. Dakshayani and N. S. Gopinath, ISRO Satellite Centre, India

This paper presents an investigation of the accuracy of the patched conic orbit with respect to the perturbed orbit for Mars missions. In patched conic approach the entire trajectory from Earth to Mars is treated as a two body problem. But, in reality the spacecraft is attracted by more than one body. For precise orbit the relevant perturbations have to be considered. Comparison of the two approaches is carried out for MRO orbit. Considerable differences are noticed between the two approaches. Even though the patched conic approach is simple to use for accurate calculation it is required to use perturbed orbit which represent the orbit more precisely.

SESSION 5: ORBIT DETERMINATION AND TRACKING - I
Chair: Mr. Bob Glover, AT&T

AAS 07 – 282
A Non-Iterative Solution for Kepler's Equation

James D. Turner, Texas A&M University

Kepler's Equation is solved over the entire range of elliptic and parabolic motion. The *M-e* plane has four domains where analytic starting values are developed for the Eccentric Anomaly by using perturbation methods. A closed-form solution is obtained for the parabolic special case by dividing the parabolic range into three independent ranges as a function of the Eccentric Anomaly, where series solution are obtained. A rapidly converging variable-order refinement algorithm, based on an analytic continuation of Newton's method, is presented. The refinement algorithm maintains a minimum of thirteen digits of precision over the entire range of elliptic and parabolic motion.

AAS 07 – 283
Assessment of the Solar Radiation Model for GRACE Orbit Determination

Minkang Cheng, John C. Ries and Byron D. Tapley, University of Texas at Austin

The GRACE (Gravity Recovery And Climate Experiment) mission is designed to determine the mean and time variable components of the Earth's gravity field. The high-accuracy accelerometer (ACC) data carried by the GRACE satellites are particularly well-suited for aeronomy study. The uncertainty in modeling of the solar radiation pressure on the GRACE satellites has been a principal concern in extracting the upper atmosphere mass density and thermospheric winds from the ACC data. This paper will present a critical assessment of the uncertainty in the GRACE macro-model for solar radiation forcing on GRACE using the calibrated accelerometer data, and its effects on determination of the upper atmosphere mass density and thermospheric winds.

AAS 07 – 284
CARTOSAT-1 Orbit Determination System and Achieved Accuracy during Early Phase

Naryanasetti Venkata Vighnesam, Anatta Sonney, Pramod Kumar Soni
and B. P. Dakshayani, ISRO Satellite Centre, India

The 1560 kg IRS-P5/CARTOSAT-1 Indian Remote Sensing Satellite (IRS) was injected by the PSLV-C6 from Sriharikota on 5th May 2005 at 10:32 IST. The satellite was put into an almost nominal orbit of (616 X 641) km with an inclination of 97.91 deg. The imaging system of CARTOSAT-1 consists of two panchromatic cameras. This paper describes the performance of orbit determination (OD) system during initial phase operations of CARTOSAT-1 mission. Achieved OD accuracy using S-band tracking data during initial phase of the mission was studied in detail. This paper highlights the achieved orbit determination accuracy based on "difference in position" method and also by comparison with SPS/GPS (Satellite Position System (SPS) 8-channel GPS receiver) orbit determination results.

AAS 07 – 285

GEO Maneuver Detection for Space Situational Awareness

Zachary J. Folcik and Richard I. Abbot, MIT Lincoln Laboratory;
Paul J. Cefola, Massachusetts Institute of Technology

This paper summarizes work done in an effort to develop a near-real time automated GEO satellite maneuver detection algorithm. Discussion and results for intermediate algorithms and a hybrid maneuver detection algorithm are included. Results for the hybrid algorithm are presented for 17 satellites over 194 days with a total of 590 known maneuvers. 94% of the maneuvers tested are detected within three days of occurrence and the average detection lag time for those detected maneuvers was one day. 49 or 8% of the total number of known maneuvers were false alarms, i.e., occurring more than three days from known maneuvers.

AAS 07 – 286

Global Positioning System Upper Stage Disposal and Collision Risk Analysis: Part 2

Alan B. Jenkin and John P. McVey, The Aerospace Corporation

Block IIF GPS EELV upper stages will remain partially in the constellation after disposal. A previous study estimated the collision risk posed to the operational constellation by the upper stages for one of the two EELV configurations. The study has since been significantly updated to account for upper stages left by both EELV configurations. Since long-term eccentricity growth is very sensitive to the initial conditions of the disposal orbit, it is necessary to account for the statistical spread in the initial conditions. The Monte Carlo procedure used in the original study to quantify this statistical variation has been improved.

AAS 07 – 287

Radar-Optical Observation Mix

Felix R. Hoots, The Aerospace Corporation

Deep space satellites can be tracked by either radar or optical sensors. However, in the US Space Surveillance Network only a limited amount of radar tracking resources is available. It would be useful to have a quantitative way to decide how to best distribute radar and optical resources to optimize the resulting orbit prediction accuracy. The covariance provides a generally accepted way to assess prediction quality. For circular satellite motion synchronized with the Earth motion, we are able to formulate the covariance analytically. The formulation allows determination of the optimum choice of resource use between radar and optical measurements. It also reveals that the optimum mix depends not only on sensor quality but also on fit span length.

AAS 07 – 288

Special Perturbations Uncorrelated Track Processing

James G. Miller, The MITRE Corporation

Two historical uncorrelated track (UCT) processing approaches have been employed using general perturbations (GP) orbit determination theory. The Cuthbert-Morris algorithm clusters UCTs based on plane, drift rate of the right ascension of the ascending node, and period matching. A pattern recognition tool developed by Lockheed Martin finds patterns in the trends of GP UCT element set parameters over time. A new special perturbations (SP) hierarchical agglomerative clustering algorithm and SP track-oriented multiple hypothesis tracking (MHT) algorithm are considered for SP UCT processing. Both SP UCT processing algorithms show improved performance over the GP UCT processing algorithms for a stressing test case.

SESSION 6: ATTITUDE DYNAMICS, DETERMINATION AND CONTROL - I
Chair: Dr. Anil Rao, University of Florida

AAS 07 – 289
Withdrawn

AAS 07 – 290

Attitude Dynamics and Control of a Compound Solar Sail

Anna D. Guerman, University of Beira Interior, Portugal;
Gueorgiy Smirnov, University of Porto, Portugal;
M. C. Pereira, Instituto Nacional de Pesquisas Espaciais, Brazil

We study attitude dynamics and control of a solar sail composed by a parabolic surface and a small flat control mirror. We develop a model of the attitude dynamics of this sailcraft, deducing the expressions for solar radiation force and torque valid also for the case of misalignment of the sail axis from the Sun direction. We also study the compound sailcraft with non-ideal collector, taking into account the irregularities of its shape. We consider and discuss various sailcraft attitude control systems based on displacement of a centre of solar radiation pressure with respect to a fixed centre of mass by a system of small vanes, stabilization by rotation and control by displacement of the sailcraft's centre of mass.

AAS 07 – 291
Withdrawn

AAS 07 – 292
Withdrawn

AAS 07 – 293

Autonomous Line-of-Sight Estimation Architectural Design for Next Generation GEO IR Payload

Peter C. Lai and Edward Fiorelli, Northrop Grumman Electronic Systems

Line-of-sight (LOS) knowledge is critical for next generation geostationary infra-red sensor payload because of increasingly stringent image accuracy requirement. Improvements can be extended when LOS determination is performed on-board and used to assist spacecraft attitude control and reduce base motion jitter transmitted to payload. This paper describes three different LOS determination designs currently being developed. The first two couple an IRU, star trackers, and IR sensor to drive a Kalman filter for enhanced LOS determination. In the third design the star tracker is eliminated and LOS knowledge is obtained using only an IRU and the IR sensor, which has the benefit of cost reduction on star trackers. The design trade starts with the steady-state solution by a covariance analysis and followed by high-fidelity LOS determination simulation.

AAS 07 – 294

Parameters Estimation of a Satellite Attitude Control Simulator

Luiz Carlos Gadelha DeSouza, National Institute for Space Research, INPE, Brazil

This paper presents the development of a Satellite Attitude Control System Simulator (SACS S) model, which allows the experimental verification of fundamental aspects of the satellite attitude dynamics and the design of different attitude control techniques, conjugated with parameters identification process. The model consists of the equation of motion which describes the satellite rotation around the vertical, with one reaction wheel as actuator and one angular velocity sensor. The parameters estimation has been done initially by the least squares algorithm in regressive form, alternatively, a recursive least squares estimation is done. Both methods have estimated the parameters with errors below the requirements, validating the platform model.

AAS 07 – 295

Survey of Calibration Algorithms for Spacecraft Attitude Sensors and Gyros

Mark E. Pittelkau, Aerospace Control Systems Engineering and Research, LLC

This paper is a survey of algorithms for ground-based and on-orbit calibration of attitude sensors and gyros on spacecraft. These algorithms include the classical Davenport gyro calibration algorithm and various Extended Kalman Filters. The calibration algorithms are outlined and compared. The operational considerations and the calibration maneuvers required for calibration are discussed. The future of on-board real-time calibration is also discussed.

SESSION 7: SATELLITE CONSTELLATIONS AND FORMATION FLYING - II
Chair: Dr. Rao Vadali, Texas A&M University

AAS 07 – 296
A Methodology Unifying Bang-Bang Controls and Low-Thrust Trajectories for the Reconfiguration of Spacecraft Formations

Laura Garcia-Taberner, Universitat de Girona, Spain;
Josep J. Masdemont, Universitat Politècnica de Catalunya, Spain

This paper addresses the reconfiguration and deployment of spacecraft formations using a systematic methodology based on the finite element method. The approach is formulated via an optimal control problem that can be tuned either to converge towards the optimal bang-bang trajectory (for the cases where the reconfiguration is far from a collision risk) or to low-thrust arcs in general situations. Illustrative examples of deployment and reconfigurations are presented with scenarios located in the Sun-Earth libration point regime and in free space. However, the methodology can also be applied to formation flying about the Earth with minor changes.

AAS 07 – 297
Perturbations of Gravity Field on a Flight Formation for an Eccentric Reference Frame

Jordi Fontdecaba Baig, Gilles Métris, F. Deleflie and Pierre Exertier,
Côte d'Azur Observatory, France

This paper presents an analytical solution for the relative motion perturbed by the gravity field of the central body. This result has been obtained using the differences of the orbital elements of the two bodies as variables for the temporal extrapolation of the relative motion. Resulting motion is projected in the local orbital frame in terms of Cartesian elements. The gravity field is analytically modelled using Kaula's development. Resulting equations are a useful tool to understand the capabilities of GRACE mission and to explore the configuration of future flight formation missions dedicated to gravity field determination.

AAS 07 – 298
Development and Control Scheme Solution for the Perturbed Motion of a Constellation in an Elliptical Orbit

Pedro A. Capó-Lugo and Peter M. Bainum, Howard University

The correction of the separation distance drifts between a pair of satellites in an elliptical orbit has been defined for different kinds of problems. The linearized Tschauner-Hempel equations are used to represent the motion of a pair of satellites in an elliptical orbit about the Earth. The objective of this paper is to present a different form of the linerized Tschauner-Hempel equations in which the linear J2 perturbation is also presented in the formulation. This formulation will be applied to a different linear quadratic regulator that will take into account the non-linearities due to the linear J2 perturbation.

AAS 07-299
Withdrawn

AAS 07 – 300
Fuel-Equivalent Relative Orbit Element Space

Jean-Francois Hamel and Jean de Lafontaine, Universite de Sherbrooke, Canada

This paper presents a new tool to analytically perform the guidance for reconfiguration of formation flying spacecraft. The technique consists in mapping the relative orbit elements into a fuel-equivalent space where similar displacements correspond to an equivalent fuel-consumption. The minimal-fuel maneuver problem is consequently translated into a simple geometric problem in the fuel-equivalent space. The theory is applied to two well-known formations: the J_2-invariant formation and the projected circular formation. The use of the fuel-equivalent space leads to very simple solutions for the most fuel-efficient way to attain both formations.

AAS 07 – 301
Linearized Dynamics of Formation Flying Spacecraft on a J_2-Perturbed Elliptical Orbit

Jean-Francois Hamel and Jean de Lafontaine, Universite de Sherbrooke, Canada

A linearized set of equations of relative motion about a J_2-perturbed elliptical reference orbit is developed. This model uses analytical relations that are well suited for on-board applications. The model uses the linearized differential drift rate of mean orbital elements to predict the impact of the J_2 perturbation on relative osculating spacecraft motion. It analytically provides the relative motion in Hill coordinates at any given true anomaly using only the initial osculating relative orbit elements and the initial orbit elements of the reference trajectory. Simulation results show that relative motion prediction remains accurate over several orbits.

AAS 07 – 302
Optimal Interferometric Image Acquisition via Multi-Spacecraft Formation Maneuvering – Special Cases of Optimality

Haithem A. Al-Twaijry, King Abdulaziz City for Science & Technology, Saudi Arabia; David C. Hyland, Texas A&M University

A brief account of image synthesis via interferometry using collected light beams from selected pairs of telescopes that are part of a formation of free-flying telescopes is presented. A measure of image quality is adopted that incorporates the estimated image and accounts for the optical performance and geometry of the telescopes. Acceptable image quality is achieved when the MTF assumes sufficient magnitudes everywhere within the *resolution disc* in the spatial resolution plane of the equivalent optical system. The problem is thus a coverage problem where we formulate and find the necessary conditions for optimality and specialize them to distinct cases relevant to the multi-spacecraft imaging situation.

AAS 07 – 303

Efficient, Passively Orbiting Constellations for High Resolution Imaging of Geosynchronous Objects

David C. Hyland, Texas A&M University

Over the past several years, much progress has been made in the development of the *Intensity Correlation Imaging* approach to ultra-fine resolution imaging. In this paper, we consider the design of a LEO-based observatory of small telescopes using the Intensity Correlation Imaging technology to achieve 1 cm resolution imaging of objects in geosynchronous orbit. We formulate the system Modulation Transfer Function (MTF) and then seek to optimize u-v plane coverage by the design of passive, LEO orbits. An adaptive random search technique is used to find constellation designs that offer twice the rate of u-v coverage as earlier results.

SESSION 8: ATMOSPHERIC RE-ENTRY GUIDANCE AND CONTROL

Chair: Dr. Paul Williams, RMIT University

AAS 07 – 304

3 -D Trajectory Optimization Satisfying Waypoints and No-Fly Zone Constraints

Timothy R. Jorris and Richard G. Cobb, Air Force Institute of Technology

Minimum time to target is the Global Strike mission of the Common Aero Vehicle. Additional mission objectives include passage through intermediate waypoints and avoidance of no-fly zones. This presentation addresses autonomous computation of a time optimal trajectory satisfying both the mission objectives and vehicle dynamic constraints. Due to the hypersonic velocity during reentry, the turn radii are significant, thus a direct point-to-point method is clearly sub-optimal. The research herein demonstrates multiple solution techniques. The 3-D model includes first-order approximations of the equations-of-motion to expedite solution convergence. The costate time histories are analyzed to verify the optimality of the solution.

AAS 07 – 305

Six-Degree-of-Freedom Trajectory Optimization for Reusable Launch Vehicle Footprint Determination

Kevin P. Bollino and I. Michael Ross, Naval Postgraduate School;
David B. Doman, Air Force Research Laboratory

In this paper, a pseudospectral (PS) method is used to solve a six-degree-of-freedom (6-DOF) trajectory optimization problem for reusable launch vehicle footprint determination. The approach is based on optimal control theory and entails the development of a high-fidelity model that addresses an important issue in model fidelity and its impact on safety. Directly solving the full 6-DOF reentry problem without relying on time- scale separation offers a more simplified and direct approach. Results show similar trajectory trends when compared to lower-fidelity solutions, but differences in extremals can be upwards of 4.5%, enough to be catastrophic if trusted as feasible landing sites.

AAS 07 – 306

Optimal Trajectories for Maneuvering Re-entry Vehicles

Aditya Undurti, Ronald J. Proulx, Roy H. Setturlund and James A. Shearer,
The Charles Stark Draper Laboratory

Many demanding aerospace missions today require maneuverable re-entry vehicles that can fly trajectories that have stringent path and terminal constraints, including those that cannot be written as drag or energy constraints. This work presents a method based on trajectory optimization techniques to assess the capabilities of the re-entry vehicle by computing the landing and re-entry footprints while meeting these conditions. The models used also account for important non-linear effects seen during hypersonic flight. Several different vehicles are studied, and the effects of parameters such the maximum G-loading, stagnation point heat rate, and the maximum L/D are analyzed.

AAS 07 – 307

Trajectory and Aerothermodynamic Analysis of Towed-Ballute Aerocapture Using Direct Simulation Monte Carlo

Kristin L. Gates Medlock, Alina A. Alexeenko and James M. Longuski,
Purdue University

Ballutes permit aerocapture at higher altitudes, lower heat fluxes, and for lower mass than traditional aeroshells. Because the velocity change is achieved at relatively high altitudes, rarefaction can be considerable and it is therefore important that analysis be conducted using the Direct Simulation Monte Carlo (DSMC) method. We investigate the aerothermodynamics of toroidal towed-ballutes for aerocapture at Venus, Mars, Neptune, and Titan. In each case, computational results for surface and flow-field interactions are presented. This study further confirms the great potential that ballute aerocapture offers for the exploration of atmosphere-bearing bodies in the solar system.

AAS 07 – 308

Analytical Atmospheric Guidance for Aerocapture

Jordi Casoliva and Kenneth D. Mease, University of California, Irvine

The aerocapture guidance is divided into two phases: (i) a capture phase and (ii) an exit phase. In the capture phase, an equilibrium glide condition is established via tracking. The exit phase initiation and guidance are based on an approximate analytical solution to the equations of motion, obtained via the method of Matched Asymptotic Expansions (MAE). For low lift-to-drag ratios, the zeroth-order inner solution is inaccurate. A new inner solution is proposed and tested, that allows lift-up and lift-down trajectories during the exit phase.

AAS 07 – 309

Entry Trajectory Planning for Higher Elevation Landing

J. Benito and K. D. Mease, University of California, Irvine

A desired capability driving Mars entry, descent and landing technology development is landing at higher elevation sites. The challenge for entry guidance is to compensate for off-nominal atmospheric conditions and vehicle aerodynamics and achieve the required vertical and horizontal delivery accuracies, despite reduced control capability due to the higher parachute deployment altitude. A new entry trajectory planner based on insight from trajectory optimization is presented and compared to other existing planners by implementing each in a common guidance algorithm and simulating entries for a variety of off-nominal conditions. The results show that the new planner allows improved guidance performance.

AAS 07 – 310

Mars Pinpoint Landing Systems Trades

Aron Wolf, Evgeniy Sklyanskiy, Jeffrey Tooley and Brian Rush,
Jet Propulsion Laboratory

Estimated landing accuracy at Mars has steadily improved, from within ~150 km of the target (3-sigma) for Mars Pathfinder to ~35 km for MER (both of which flew unguided ballistic entries), mainly due to improved approach navigation. The 2009 MSL mission will improve delivery to within ~10 km using guided hypersonic entry to "fly out" atmospheric and vehicle aerodynamics uncertainties. "Pinpoint Landing" within 100 m requires terrain-relative navigation, as well as additional propellant in powered descent which levies a penalty on EDL performance. Systems trades affecting this propellant mass penalty are explored here.

AAS 07 – 311

Precision Entry Navigation Dead-Reckoning Error Analysis: Theoretical Foundations of the Discrete-Time Case

Renato Zanetti and Robert H. Bishop, The University of Texas at Austin

A linear covariance analysis strategy is developed for application to atmospheric planetary entry where the only available navigation data is provided by strapdown inertial measurement units. The navigation scenario considered encompasses the so-called dead-reckoning navigation wherein the inertial measurement unit provides measures of the change in velocity and the change in attitude at discrete times. These measurements are used to propagate an initial state estimate forward in time. The question that is addressed is quantifying the accuracy of the state estimate using dead-reckoning during a typical Mars atmospheric entry. The inertial measurement data is assumed to be corrupted with random noise, random constant biases, misalignment errors, and scale factor errors, and the location of the spacecraft center of mass is also considered to contain uncertainty.

SESSION 9: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL - I
Chair: Dr. Thomas Lovell, Air Force Research Laboratory

AAS 07 – 312
Autonomous Lunar Orbit Navigation Using Optical Sensors

Sun Hur-Diaz, Bill Bamford and Dave Gaylor, Emergent Space Technologies, Inc.

Autonomous use of optical sensors for obtaining self-contained navigation solutions in a lunar orbit that are independent of ground or other external aids is explored. Tracking of multiple unknown landmarks on the Moon is considered along with a disk measurement providing range information from infrared sensors. Sensitivity of the navigation performance to sensor accuracy, number of landmarks, measurement frequency, and initial error is assessed. Navigation performance obtained from tracking unknown landmarks is compared with performance obtained from tracking known landmarks.

AAS 07 – 313
Guidance and Navigation Linear Covariance Analysis for Lunar Powered Descent

Travis J. Moesser and David K. Geller, Utah State University

A linear covariance analysis tool is presented for use in assessing the performance of guidance, navigation, and control (GN&C) systems of the Lunar Surface Access Module (LSAM) during lunar powered descent, incorporating Autonomous Landing Hazard and Avoidance Technology (ALHAT). Guidance algorithms designed for lunar landing are presented and incorporated into the closed-loop covariance equations. Event triggering is also included in the covariance formulation to use navigation knowledge in dispersion control. Several studies are presented, including an inertial-only navigation study, a final approach navigation study, and dispersion control studies with triggering and guidance.

AAS 07 – 314
Precision Descent Navigation for Landing at the Moon

Kyle J. DeMars and Robert H. Bishop, The University of Texas at Austin

A detailed analysis of the algorithm for precision descent navigation is presented. A continuous-discrete, dual-state extended Kalman filter is developed in which the position, velocity, and attitude of the vehicle constitute one state in the dual-state realization, and the selected landing site constitutes the second state in the dual-state realization. Concurrently, estimation of the errors associated with accelerometer and gyro based measurements, as well as the errors associated with external sensor measurements (such as altimetry and velocimetry), is performed. Additionally, deviations from the nominal position of the center of gravity of the vehicle with respect to the inertial measurement unit are estimated.

AAS 07 – 315

Mars Reconnaissance Orbiter Primary Science Orbit Acquisition

Ramachandra S. Bhat, C. Allen Halsell, Tung-Han You, Stacia M. Long, Dolan E. Highsmith, Stuart W. Demcak, Eric J. Graat, Neil A. Mottinger and Earl S. Higa, Jet Propulsion Laboratory

A sequence of five maneuvers was designed and implemented to achieve the Primary Science Orbit after the termination of Mars Reconnaissance Orbiter (MRO) aerobraking on August 30, 2006. These maneuvers adjusted the size of the orbit, corrected the inclination, rotated the apsidal line to get the frozen conditions, acquired the required ground tack walk pattern, and froze the Local Mean Solar Time (LMST) of the ascending node at the desired time (3:00 PM ± 15 Min). The five maneuver sequence was successfully completed on December 13, 2006 providing smooth transition to the Primary Science Phase. The achieved Local Mean Solar Time was 3:02:39 PM and achieved the required ground track walk pattern.

AAS 07 – 316

State Estimation and Targeting for Autonomous Rendezvous and Proximity Operations

Scott C. Jenkins and David K. Geller, Utah State University

There is a recent trend toward developing autonomous rendezvous and proximity operation capabilities, as observed by the ETS-VII, XSS -11, Dart, and Orbital Express missions. This paper presents the comparison of inertial versus relative navigation and targeting systems for orbital rendezvous and proximity operations. Since both methods can be used, the situations where one method works better than the other has not been resolved. The development of the navigation and targeting algorithms for each system are presented. Results include the relative trajectory control errors, navigation errors and required CPU time simulated for a variety of rendezvous situations.

AAS 07 – 317

Withdrawn

AAS 07 – 318

Optimal Formation Deployment Using Relative Constraints

Michael Volle, a.i. solutions, Inc.

This paper examines a method of optimizing the deployment of a formation of spacecraft about a reference halo orbit using relative dynamics and relative targeting conditions. The equations of motion relative to the reference halo orbit are derived and calculated in a rotating frame. The relative targeting conditions are used to specify an arbitrary formation size and shape, and zero relative velocity. Indirect methods of optimization are used to form a time-constrained, finite-burn, minimum fuel problem. Two sets of controls are considered, as well as the evolution of the formation after the deployment.

AAS 07 – 319

Reconstruction of the Voyager Uranus Encounter in the ICRF System

Robert A. Jacobson and Brian P. Rush, Jet Propulsion Laboratory

The Uranian system was visited by the Voyager~2 spacecraft in January of 1986. Taylor *et al.* (AIAA Paper 86-2112) discusses the determination of the spacecraft's orbit. In 2007 the planes of Uranian satellite and ring system will appear edge on as viewed from the Earth. This geometry provides astronomers a unique observational opportunity. Data acquired during 2007 will be analyzed together with previous observations such as those obtained by Voyager. To enhance the scientific study of the Uranian system, we have re-examined the Voyager mission. We obtain a revised Voyager trajectory and an updated the Uranian system gravity field.

SESSION 10: TRAJECTORY DESIGN AND PLANETARY MISSION STUDIES - II

Chair: Dr. Louis D'Amario, Jet Propulsion Laboratory

AAS 07 – 320

Analysis of Capture Trajectories to the Periodic Orbits in the Vicinity of Libration Points

Masaki Nakamiya, The Graduate University for Advanced Studies, Japan;
Daniel J. Scheeres, University of Michigan;
Hiroshi Yamakawa, Kyoto University, Japan;
Makoto Yoshikawa, Japan Aerospace Exploration Agency, Japan

We investigate spacecraft capture trajectories to the periodic orbits in the vicinity of the L1 and L2 points in the restricted Hill three-body problem. The specific focus is on transfer into these vicinities from interplanetary trajectories. This application is motivated by future plans to use the Sun-Earth and Sun-Mars collinear libration points as a space hub for Mars Mission. We analyze the feasibility of using aero-assist capture to reduce the cost of transfer into these locations.

AAS 07 – 321

Numerical Parametrizations of Libration Point Trajectories and Their Invariant Manifolds

Josep M. Mondelo, IEEC & Universitat Autonòma de Barcelona, Spain;
Esther Barrabés, Universitat de Girona, Spain;
Gerard Gómez, IEEC & Universitat de Barcelona, Spain;
Mercè Ollé, Universitat Politecnica de Catalunya, Spain

The present paper is devoted to the development of a methodology for the numerical parametrization of all the trajectories (periodic orbits and 2D tori) in a large neighborhood of the collinear libration points of the restricted Three-Body Problem, as well as their invariant stable and unstable manifolds. The methodology is based in interpolation of a sufficiently fine mesh of individual trajectories and manifolds obtained by numerical continuation. In this way, the convergence restrictions of semi-analytical techniques, such as Lindsted-Poincaré expansions, are avoided. Numerical results will be shown for the L1 and L2 points of the Earth-Moon and Sun-(Earth+Moon) systems.

AAS 07 – 322
Withdrawn

AAS 07 – 323
Withdrawn

AAS 07 – 324

Interplanetary Waveriders for Atmospheric Sample Return

Daniel T. Lyons and Evgeniy Sklyanskiy, Jet Propulsion Laboratory

Interplanetary Waveriders use atmospheric lift to increase the effectiveness of gravity assist maneuvers by increasing the bending angle at the expense of departure speed. A detailed simulation of the atmospheric flyby segments of a possible waverider based, atmospheric sample return mission to Mars and Venus evaluates the possible difficulties associated with achieving and controlling such trajectories. The high departure speeds require very accurate targeting of both the departure speed and direction to minimize cleanup propellant requirements. Preliminary results show that the perturbed, integrated simulations of the atmospheric flight segments can achieve the departure V-infinity targets from the reference interplanetary design.

AAS 07 – 325

Optimization of Aerogravity-Assist Trajectories for Waveriders

Gregory A. Henning, and James M. Longuski, Purdue University

Aerogravity-assist (AGA) and waverider research has demonstrated the potential to deliver spacecraft to a wide range of destinations within the solar system. We use patched conics for a fixed L/D during the AGA to obtain boundary conditions at the flyby planets. For the assumed L/D, the flythrough departure velocity is maximized while meeting the required atmospheric turn angle. After this step, the departure velocity is usually greater than required, allowing us to reduce the L/D to a minimum in the final step. As an example, we design an Earth departure and return mission with flybys at Mars and Venus (EMVE).

AAS 07 – 326

Preliminary Speculation on Accretion Mechanism Associated with 'Rubble Pile' Celestial Objects

Jun'ichiro Kawaguchi, ISAS/JAXA, Japan; Akifumi Kitajima, Yuichi Miwa and Masatoshi Hiyabayashi, University of Tokyo, Japan

Itokawa visited by Hayabusa belongs to the 'Rubble Pile' category, which accumulated fragments that derived from the collision between larger celestial bodies. Here is left a simple question as to the formation process. It is on whether Itokawa's shape is a typical Rubble Pile shape. The asteroids so far visited have shown different shapes and the answer to it apparently seems incorrect. However, the paper will look into the accretion process about such irregular shape bodies, and try to present a certain, but still preliminary, evolution mechanism and stories.

AAS 07 – 413

Application of the Weierstrass Condition in Rocket Trajectory Optimization

David G. Hull, University of Texas at Austin

The singular, variable-thrust subarc of an optimal chemical rocket trajectory was shown to be minimizing by applying the Weierstrass condition (WC). Subsequently, the generalized Legendre-Clebsch conditon (GLCC) was developed which proved that the variable-thrust subarc was non-minimizing. This contradiction is explained by showing that the WC does not apply on a singular arc. A strong point condition (SPC) is developed and is shown for a singular control to reduce to the form of the GLCC, so that both conditions yield the same result. The WC and SPC are applied to the chemical rocket problem directly and by redefining the controls to convert a singular problem into a non-singular problem. Results are also presented for an electric rocket operating at maximum power.

SESSION 11: SPECIAL SESSION - 50 YEARS OF SPACE DEVELOPMENT
Chairs: Dr. Thomas Eller, Astro USA, LLC
Dr. Tony Hagar, Embry-Riddle Aeronautical University

AAS 07 – 327

A Brief History of NRL's Early Firsts in Spaceflight

Patrick W. Binning and Jay W. Middour, Naval Research Laboratory

The Naval Research Laboratory has been a pioneer in our nation's exploration of spaceflight starting from being competitively selected in 1955 by the National Science Foundation to launch America's first spacecraft, to the current participation in America's policy for Operationally Responsive Space. It is true that NRL did not achieve orbit first for America, however, NRL continues to lay claim to having built and launched human-kind's oldest orbiting object, Vanguard I. A brief history will be explored of NRL's many legacies to spaceflight; the Vanguard Program, NRL's contribution to the formation of NASA and the Goddard Space Flight Center, America's first reconnaissance satellite, GRAB [declassified in June, 1998], as well as defining moments in the NRL inventions of the Naval Space Surveillance System and the Global Positioning System.

AAS 07 – 328

50 Years of Satellite Tracking and Cataloging in the US

Felix R. Hoots, The Aerospace Corporation; Paul W. Schumacher, High Performance Computing Software Applications Institute for Space Situational Awareness;
Taft DeVere, 1st Space Control Squadron

The launch of the Sputnik satellite in 1957 created a need within the United States to track and maintain a catalog of orbital elements for artificial Earth satellites. The key components in the historical development of this processing are: a worldwide system of observing sites that provides the tracking data of the satellites, the cataloging and updating of orbital elements on each satellite, the analytical orbit prediction models, and the people who fashioned the process out of whole cloth evolving and inventing a solution to a problem that did not even exist prior to 1957.

AAS 07 – 329
Withdrawn

AAS 07 – 330

Apollo 13 Trajectory Reconstruction via State Transition Matrices

Daniel R. Adamo, United Space Alliance, LLC

An iterative method of solving the perturbed Lambert boundary value problem using state transition matrices is documented and applied to reconstructing Apollo 13's as-flown trajectory. Use of NASA Apollo Trajectory (NAT) elements as Lambert boundary values is validated. Abridged NAT element tables appear to be the only comprehensive as-flown Apollo Program trajectory data available to present-day researchers. In their application to trajectory reconstruction, NAT elements are of great value to space historians and NASA's Vision for Space Exploration.

AAS 07 – 331

A History of Tethers in Space: Innovative Concepts, Technical Developments, and Missions

Paul A. Penzo, Global Aerospace Corporation;
Arun K. Misra, McGill University, Canada

The first serious interest in space tethers began when the Tethered Satellite System (TSS) was proposed to NASA and the Italian Space Agency (ASI) in the early 1970's. An agreement was signed in 1984 where NASA would build a deployer system, and ASI would develop a special satellite for deployment. With the many unknowns associated with this mission, the NASA Office of Space Flight Advanced Projects formed the Tether Application in Space (TAS) Task Group to investigate other possible tether mission concepts and technical requirements. This became a major effort, involving the aerospace industry, universities, and government. For the next 10 years or so, with increasing general interest, many workshops, conferences, and special meetings were held in both countries. This paper summarizes these many activities.

AAS 07 – 332
Withdrawn

AAS 07 – 333
Withdrawn

AAS 07 – 334

Historical Development of the Transit Satellite Navigation Program

Thomas Thompson, Johns Hopkins University Applied Physics Laboratory

The genesis of the *Transit* satellite navigation program at the Applied Physics Laboratory evolved as a direct result of an experiment in the tracking of telemetry signals from the Sputnik I satellite. Although the concepts of orbit determination and station location estimation were clear, many engineering challenges lay ahead with knowledge of the space environment not well known, the gravity field of the earth was not well determined and satellite engineering was in its infancy with many who believed that the spacecraft engineering could not be practically accomplished. This article will review the *Transit* system development, the evolution of the ideas that established the fundamentals of satellite navigation and positioning, and the technological advances realized within the program history.

SESSION 12: ATTITUDE DYNAMICS, DETERMINATION AND CONTROL - II

Chair: Dr. Mark Pittelkau, Aerospace Control Systems Engineering and Research, LLC

AAS 07 – 335

Rotational Dynamics of a Comet Nucleus Subject to Outgassing Jets

Sharyl M. Byram and Daniel J. Scheeres, University of Michigan

A model for the dynamical evolution of a comet nucleus rotation state is presented in support of spacecraft navigation for future comet missions. The model predicts possible levels of rotational excitation and estimates the possible change in rotation state during a perihelion passage which arise as the result of multiple discrete outgassing jets acting on the nucleus. Each jet is modelled as an emission cone while the comet body is modelled as a uniform density ellipsoid. Two computational methods for integrating the comet's rotational dynamics under outgassing pressures are compared, a variational integrator and a standard RK method.

AAS 07 – 336

Spin Axis Estimation with RF Hardware - A Solar Sentinels Case Study

Wayne F. Dellinger and Dipak K. Srinivasan,
The Johns Hopkins University Applied Physics Laboratory

Two methods of using a spacecraft's radio frequency telecommunication system along with a Sun sensor for spin-axis estimation are presented. One method uses the platform rotation and gimbal angles of a de-spun high-gain antenna platform, and the other uses the measured sinusoidal Doppler shift of an antenna off-set from the spin axis. These two methods give the earth angle that, along with a measured sun angle, provide the necessary vectors for attitude estimation. Simulated performance results are presented using the Solar Sentinels mission, a proposed constellation consisting of multiple ecliptic-normal spinning spacecraft to study the Sun.

AAS 07 – 337

Implementation of a Multiplicative Extended Kalman Filter (MEKF) for Spinning Spacecraft Attitude Determination in the Astrodynamics Environment (ADE)

Kenneth J. Ernandes and Benjamin E. Joseph, Braxton Technologies, Inc.;
Paul J. Cefola, MIT

Recently a Kalman filter was developed in the Braxton Technologies Astrodynamics Design Environment (ADE) software for spin-stabilized Attitude Determination (AD) computations. This paper provides a brief description of the filter design and illustrates the functionality of Braxton's attitude filter by comparing its performance against two already existing systems: the NASA Goddard Space Flight Center (GSFC) Multimission Spin-Axis Stabilized Spacecraft (MSASS) Attitude Determination System (ADS) and the Air Force's Command and Control Segment (CCS) systems. Comparison is based upon convergence rate, accuracy, and robustness from actual attitude data from a spin-stabilized spacecraft. Real data cases are included.

AAS 07 – 338

Zero Gyro Kalman Filtering in the Presence of a Reaction Wheel Failure

Sun Hur-Diaz, Emergent Space Technologies, Inc.;
John Wirzburger, Honeywell Technology Solutions, Inc.;
Dan Smith, Lockheed Martin Mission Services;
Mike Myslinski, Honeywell Technology Solutions, Inc.

Typical implementation of Kalman filters for spacecraft attitude estimation involves the use of gyros for three-axis rate measurements. When there are less than three axes of information available, the accuracy of the Kalman filter depends highly on the accuracy of the dynamics model. This is particularly significant during the transient period when a reaction wheel with a high momentum fails, is taken off-line, and spins down. This paper looks at how a reaction wheel failure can affect the zero-gyro Kalman filter performance for the Hubble Space Telescope and what steps are taken to minimize its impact.

AAS 07 – 339

Internal Disturbance Accommodation Filter of Control Moment Gyros with Adaptive Observer

Masaki Takahashi and Seiichi Shimizu, Keio University, Japan;
Shigemune Taniwaki, Ehime University, Japan;
Yoshiaki Ohkami and Kazuo Yoshida, Keio University, Japan

The objective of this study is to establish the high accurate pointing control method of the satellite with CMG while taking a photograph of the ground target. In the method after the satellite starts to maneuver, the frequency of the internal disturbance is estimated by the adaptive observer of Kreisselmeier. After the maneuver of satellite is finished, the active internal disturbance accommodation filter based on the internal model principle is established and the internal disturbance is eliminated by feed-forward control. From the simulation results, it was confirmed the usefulness of the proposed method.

AAS 07 – 340

Enhancements of Repetitive Control using Specialized FIR Zero-Phase Filter Designs

Jiangcheng Bao and Richard W. Longman, Columbia University

Repetitive control can cancel the effects of periodic disturbances on a feedback system. It can cancel the effects of jitter from imbalance in a momentum wheel on fine pointing equipment on a satellite. To produce stability robustness to residual modes, real-time zero-phase low-pass filtering must be used in practice. Improved methods of designing such filters are presented, using quadratic programming with inequality constraints, allowing one to use a higher filter cutoff. Digital control often makes use of anti-aliasing filters, and in the repetitive control application this can be zero-phase. The use of such filters in RC is also investigated.

AAS 07 – 341

The Advantages and Disadvantages of Kalman Filtering in Repetitive Control

Benjamas Panomruttanarug, King Mongkut's University of Technology, Thailand;
Richard W. Longman, Columbia University

Iterative learning control (ILC) and repetitive control (RC) can eliminate deterministic tracking errors in repeating situations. In theory, RC on an active isolation mount for fine pointing equipment can completely eliminate the effects from a vibration source such as a momentum wheel with slight imbalance. When there is plant and measurement noise it is natural to ask if Kalman filtering can improve performance. It is shown that Kalman filtering normally will introduce biases and hence there is a trade-off. Also, implementation issues are studied, and a method of approximating the Kalman smoother by an FIR filter are studied.

AAS 07 – 342

Withdrawn

SESSION 13: LOW THRUST MISSION AND TRAJECTORY DESIGN
Chair: Professor Kathleen Howell, Purdue University

AAS 07 – 343

Low-Thrust Transfers in the Earth-Moon System Including Applications to Libration Point Orbits

K. C. Howell and M. T. Ozimek, Purdue University

Preliminary designs of low-thrust transfer trajectories are developed in the Earth-Moon three-body problem. The solution for a complete time history of the thrust magnitude and direction is initially approached as a calculus of variations problem to locally maximize the final spacecraft mass. The problem is then solved directly by sequential quadratic programming using multiple shooting. The coasting phase along the transfer exploits invariant manifold theory and considers locations along the entire manifold surface for insertion. This investigation includes transfer trajectories from an Earth parking orbit to sample libration point trajectories including L_1 halo orbits, L_1 and L_2 vertical orbits, and L_2 “butterfly” orbits.

AAS 07 – 344
Withdrawn

AAS 07 – 345

Reduction of Low Thrust Continuous Controls for Trajectory Dynamics

Jennifer S. Hudson and Daniel J. Scheeres, University of Michigan

A novel coefficient-based method to evaluate the trajectory dynamics of low-thrust spacecraft is developed. The thrust vector components are represented as Fourier series in eccentric anomaly and Gauss’s variational equations are averaged over one orbit to define a set of secular equations. These secular equations are a function of only 14 of the thrust Fourier coefficients, regardless of the order of the original Fourier series, and are sufficient to determine the low-thrust spiral trajectory with significantly reduced computational requirements as compared to integration of the full Newtonian problem. This method has applications to the spacecraft targeting and optimal control problems.

AAS 07 – 346
Withdrawn

AAS 07 – 347

Station Keeping Close to Unstable Equilibrium Points with a Solar Sail

Ariadna Farrés and Àngel Jorba, Universitat de Barcelona, Spain

We have considered the movement of a Solar sail in the Sun - Earth system. Using the Circular RTBP + Solar radiation pressure as a model we have a 2D family of equilibrium points (most of them unstable) parametrised by the two angles defining the sail orientation. The knowledge of the variation of the invariant manifolds with respect to the sail orientation has permitted us to design a control strategy to keep close to one of these unstable points. This strategy has been tested for different fonts of errors and initial conditions.

AAS 07 – 348

Design Space Pruning Techniques for Low-Thrust, Multiple Asteroid Rendezvous Trajectory Design

Kristina Alemany and Robert D. Braun, Georgia Institute of Technology

In 2006, the 2nd Global Trajectory Optimization Competition (GTOC2) posed the problem of maximizing the ratio of final mass to flight time for a low-thrust trajectory which performs a rendezvous with one asteroid from each of four defined groups (resulting in over 41 billion possible asteroid combinations). One of the major weaknesses sited by participants was their lack of a rigorous method for quickly eliminating a large number of asteroids and asteroid combinations, while maintaining the best solutions in the design space. This paper examines several design space pruning techniques for a subset of the GTOC2 problem.

AAS 07 – 349

PHOIBOS Mission Analysis - A Low Thrust Trajectory Towards the Sun Corona

Régis Bertrand, Jean-Yves Prado and Emmanuel Hinglais,
Centre National d'Etudes Spatiales (CNES), France

This paper details the flight dynamics results of the PHOIBOS (Probing Heliospheric with an Inner Boundary Observing Spacecraft) study. The scientific objectives require the spacecraft to reach a very energetic heliocentric orbit with a perihelion of four solar radii and an ecliptic inclination of at least sixty degrees. These requirements are classically achieved by means of costly powerful launchers and a Jupiter gravity assist. We propose in this paper an alternative mission scenario based on the combined use of inner-planet gravity assists and electric propulsion. This cruise strategy allows to use cheaper launchers and to enhance the mission flexibility.

SESSION 14: ATTITUDE DYNAMICS, DETERMINATION AND CONTROL - III
Chair: Dr. Don Mackison, University of Colorado

AAS 07 – 350
Corresponding Point Detection by Harris Corner Detector and RANSAC, and Attitude Variation Estimation by the Eight-Point Algorithm

Hirohisa Kojima, Keitarou Kimoto and Yutaka Usuda,
Tokyo Metropolitan University, Japan

An image processing method to estimate the attitude variation of a satellite is proposed. The proposed method consists of five steps: searching the position of a target satellite in an image using color information, extraction of feature points on the satellite using a Harris corner detector, optical flow estimation by template matching and random sample consensus, deleting incorrect optical flow using the eight-point algorithm, and determination of the rotational axis and attitude variation from the optical flow by a heuristic approach. A space light simulation room is developed to emulate the light condition in space and is used to verify the validity of the proposed method. Experiments on the images of a satellite model taken in the simulation room show that the proposed method can estimate the rotational axis within a roughly 30-degree relative angle and the attitude variation of the target satellite within an error range of 3 deg.

AAS 07 – 351
Withdrawn

AAS 07 – 352
Addressing Problems of Instability in Intersample Error in Iterative Learning Control

Yao Li and Richard W. Longman, Columbia University

Iterative learning control (ILC) aims to produce zero tracking error following a specific command, by learning from experience executing that command. There are potential applications in spacecraft that use fine pointing instruments that make repeated scans. Previous work has shown that asking for zero error at every time step produces very large error between the time steps for the majority of systems. Methods are investigated to address this problem. The most effective requires using a higher sample rate and asking for zero error every other time step, as well as extending the desired trajectory at each end.

AAS 07 – 353

Design of Repetitive Controllers in the Frequency Domain for Multi-Input Multi-Output Systems

Richard W. Longman and Kevin Xu, Columbia University;
Minh Q. Phan, Dartmouth College

Momentum wheels, CMG's, reaction wheels, and cryo pumps can have slight imbalances that create vibrations in a spacecraft structure. Fine pointing equipment must be isolated from such vibrations. Repetitive control is an active control method that theoretically can completely eliminate the effects of periodic disturbances. Very effective design methods have previously been developed to design repetitive controller for single-input single-output systems. To address the spacecraft problem, these methods were generalized to handle multiple unrelated periods. Here they are further generalized to handle multi-input multi-output systems as need to isolate fine pointing equipment in all six degrees of freedom.

AAS 07 – 354

On Closed-Loop Spacecraft Attitude Maneuvers

Pooya Sekhavat and I. Michael Ross, Naval Postgraduate School

Agile spacecraft maneuvering is essential to maximize observations. In this paper, we show that commonly-used feedback control laws, including optimal eigenaxis controllers, significantly diminish observation opportunities. This conclusion is borne out by comparing various state feedback controllers versus non-eigenaxis optimal steering. The optimal steering problem is solved using pseudospectral methods. Various performance gains including faster maneuver time as well as actuator size reduction are discussed in detail. It is further shown that, unlike traditional feedback control, the Carathéodory-π optimal control exploits the potential benefits of exogenous disturbances rather than rejecting them blindly.

AAS 07 – 355

Minimum-Time Maneuvering of CMG-Driven Spacecraft

Andrew Fleming, Space and Naval Warefare Systems Command;
I. Michael Ross, Naval Postgraduate School

In this paper we address the rigid-body reorientation of a spacecraft with control moment gyros (CMGs) as the torque generating devices. The attitude and attitude rate sensors provide the initial conditions for the problem formulation which is described as a rest-to-rest maneuver in the inertial frame. The full non-Eulerian dynamics are exploited in a path-free maneuver to achieve the minimum-time maneuver. Initial gimbal position is fixed at zero for a benchmark problem. Results for a small spacecraft based on the parameters of NPSAT1 demonstrate the details of our approach.

AAS 07 – 356

Receding Horizon Control on Steering of Control Moment Gyro for Fast Attitude Maneuver

Kohei Takada and Hirohisa Kojima, Tokyo Metropolitan University, Japan

Although Control Moment Gyro has the advantage of output torque, its singularities hinder from using it on spacecrafts. While any numbers of studies on singularity avoidance have been carried out, attitude settling time in maneuver using CMG was still long. In this paper, receding horizon control was applied to CMG steering for fast attitude maneuver. The evaluation function is selected so as not to force the system to avoid all singularities. Numerical simulations show that gimbal trajectories avoiding singularities that are serious for attitude settling are selected by evaluating only attitude error, in spite of not evaluating CMG gain.

AAS 07 – 357

Relative Equilibria of a Tetrahedral Structure with Rigid and Tethered Elements

Alexander A. Burov, Dorodnicyn Computing Center of the RAS, Russia;
Anna D. Guerman, University of Beira Interior, Portugal;
Revaz S. Sulikashvili, Razmadze Mathematical Institute, Republic of Georgia

We study equilibria of a tetrahedral structure with rigid and tethered elements in a circular orbit. We discuss the possibility to use flexible tethers to provide the tetrahedron configuration. The reactions appearing the links connecting the massive points in the tetrahedral satellite constellation are studied. The objective is to identify the links which are subject to stretch and consequently can be replaced by massless tethers. We also discuss the methods of attitude control for such structures and possible geometrically based generalizations of the considered systems.

SESSION 15: ORBIT DETERMINATION AND TRACKING - II
Chair: Dr. Felix Hoots, The Aerospace Corporation

AAS 07 – 358

A Preliminary Analysis of State Vector Prediction Accuracy

David A. Vallado, Center for Space Standards and Innovation

Modern precise navigation services are creating increased applications for numerically generated state vectors for satellite operations. Traditional radar and optical techniques can achieve modest accuracy in orbit determination, but on-board GPS satellite receivers are changing the routine accuracy available. System requirements usually involve future locations, rather than past locations derived from OD techniques. This paper compares propagation of various satellite initial state vectors to independently produced Precise Orbit Ephemerides (POE's). The initial state of each satellite is varied to reflect expected orbital accuracy achievable through existing orbit determination techniques. Satellite ephemerides are compared to known POE's, and to precise ephemerides generated by state-of-the-art orbit determination techniques.

AAS 07 – 359

Artificial Damping for Stable Long-Term Orbital Covariance Propagation

J. Russell Carpenter and Kevin Berry, NASA Goddard Spaceflight Center

There are contexts in orbital navigation in which it may be advantageous to constrain the growth of the covariance. For instance, predictions of potential conjunctions may require propagation of the covariance many orbits into the future. In such applications, predictions of the uncertainty may require that the covariance propagation include process noise, which will produce unbounded growth in the covariance matrix. Eventually, the elements of the covariance matrix will exceed the precision of the computer. As a mitigation, this paper describes how the addition of an artificially damped mode, several orders of magnitude slower than the orbital dynamics, can force the covariance propagation to attain a constant steady-state value. This mode does not noticeably affect the evolution of the covariance over short time scales.

AAS 07 – 360

Radiometric Tracking Benefits of Using a Coherent Transceiver System With Flexible Turnaround Ratios

Karl B. Fielhauer, Gene A. Heyler, Christopher B. Haskins, Dipak K. Srinivasan and Christopher J. Krupiarz

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has developed a coherent transceiver system that has a reprogrammable uplink frequency and flexible downlink turn-around ratio that enables simultaneous radiometric tracking using a single antenna aperture. This novel technology will allow secondary spacecraft to track the primary spacecraft's uplink signal, operating in a different uplink channel assignment from its own for a given pass, and coherently or non-coherently turn that signal around within its own downlink channel assignment. Doing so will greatly expand the radiometric tracking data available for spacecraft navigation and science.

AAS 07 – 361
Withdrawn

AAS 07 – 362

Singular Value Decomposition and Least Squares Orbit Determination

Vladimir F. Boikov and Zakhary N. Khutorovsky, Vymple Int. Corporation, Russia;
Kyle T. Alfriend, Texas A&M University

When determining orbits from measurements with least-square techniques, it is often difficult to assure convergence when a) there are only a small number of measurements with large time intervals between the measurements (sparse measurements), b) the measurement accuracy is poor, c) there are crude or abnormal measurements present, or d) no good initial guess is available. We show in this paper how an algorithm using SVD can resolve convergence problems in these cases by choosing the dimension of the minimization subspace for each minimization step. Results are shown for LEO orbits with radar measurements.

AAS 07 – 363

Optimal Measurement Filtering and Motion Prediction Taking into Account the Atmospheric Perturbations

Andrey I. Nazarenko, Space Observation Center, Russia;
Vasiliy S. Yurasov, Institute for Precision Instrument Engineering, Russia;
Kyle T. Alfriend, Texas A&M University;
Paul J. Cefola, Massachusetts Institute of Technology

The primary errors in orbit determination and prediction for Low Earth Orbit space objects result from the inaccuracy of the upper atmosphere density models and the absence of concrete data about the variations of the ballistic factors. The authors investigate a convenient method for orbit determination taking into account 'colored noise' statistical characteristics of the atmospheric disturbances. This technique, named "Optimal Measurement Filtering" (OMF), has some common features with both the Least Squares Technique and the Kalman filter. The *a priori* correlation function of the atmospheric noise is given in the form of a numerical table.

AAS 07 – 364

Precise Orbit Determination of Satellite Using a Batch Filter Based on the Unscented Transformation

Eun-Seo Park, Sang-Young Park and Kyu-Hong Choi, Yonsei University, Korea;
Kyoung-Min Roh, GeoForschungZentrum Potsdam (GFZ), Germany

In this paper, a new batch least squares algorithm using the Unscented Transformation has been presented and utilized for satellite orbit determination. The existing batch least squares has been applied to nonlinear system by simply linearizing and approximating all the nonlinear models. These approximations cause errors in resulting accuracy and/or instability in the estimation process that can produce divergence of filters. The main object of this paper is to derive a new algorithm using the Unscented Transformation to overcome the linearization and approximation errors. An alternative generalization of the batch least squares is proposed and applied to the satellite orbit determination. The results of the new algorithm have been compared with those of existing batch least squares to evaluate the accuracy and stability performance.

AAS 07 – 365

GOCE Precise Emulator for ESOC Flight Dynamics Operations Preparation

Livio Tucci, Stefano M. Pessina and Michael L. Flegel, Terma GmbH at ESA/ESOC, Germany; Susanne Kasten-Coors, ESA/ESOC, Germany

Within the Flight Dynamics (FD) Division of the European Space Operations Centre (ESOC), an emulator has been developed by the Test & Validation group for the ESA GOCE mission. During operations preparation, the emulator is used to test the FD system and to train the whole team. In operations, the emulator validates FD commands and it is valuable in analysing AOCS performance and investigating contingencies. After an outline of the requirements for the emulator, the design and implementation approach will be presented. Additionally, the spacecraft hardware and space environment models will be described. Examples will be given about the emulator operational applications.

SESSION 16: DYNAMICS AND CONTROL OF LARGE SPACE STRUCTURES

Chair: Professor Richard Longman, Columbia University

AAS 07 – 366
Withdrawn

AAS 07 – 367

Electrodynamic Tether Shape Estimation with Square-Root Unscented Filter

Paul Williams, RMIT University, Australia

The dynamic estimation of the state of an electrodynamic tether system is considered. A square-root implementation of an unscented filter is utilized. In the first instance, a filter is developed based on an inelastic tether model, which is used to estimate the tether libration dynamics. This is coupled with a simple feedback control scheme for tracking a desired libration trajectory. A filter is also developed that takes into account the effects of tether flexibility. Only measurements of the tetherend body position and the tangent vector at the main spacecraft are required to estimate the tether shape and libration dynamics.

AAS 07 – 368

Libration Control of Electrodynamic Tethers Using Model Predictive Control with Time-Delayed Feedback

Paul Williams, RMIT University, Australia

A control strategy is developed for stabilizing electrodynamic tethers in elliptic and time-varying orbits. The control is developed by using time-delayed feedback of the system states from the previous orbit. The control input, which is assumed to be only the electric current, is selected so as to minimize a weighted cost function that trades the difference between the time-delayed trajectory and the control effort. The nonlinear optimal control problem is solved and implemented in real-time to stabilize the electrodynamic tether system in the general case of a non-fixed center of mass orbit.

AAS 07 – 369

On the Control of a Permanent Tethered Observatory at Jupiter

J. Peláez, Technical University of Madrid, Spain;
D. J. Scheeres, University of Michigan

Outer planet exploration is always handicapped by a scarcity of power. In some missions, electrodynamic tethers could be an alternative to produce the required energy. In this paper, we present a permanent Jupiter observatory located at one of its inner moonlets and sustained by an electrodynamic tether. We extend a previous analysis by using the Hill equations, and we introduce a more detailed analysis of the electrodynamic aspects of the tether. In particular we deepen in the sensitivity of the tether attitude with the changes of the tether current to establish an appropriate control law for the whole system.

AAS 07 – 370

Quick Deployment of Bare Tape Tether and Overview of the Sounding Rocket Experiment

Takeo Watanabe, Hironori A. Fujii and Hirohisa Kojima,
Tokyo Metropolitan University, Japan

In the present study, the deployment behavior of the tape tether is analyzed by observation at the on ground test rig, and the deployment drag is measured. A tower type deployment simulator device and vacuum chamber have been developed to simulate the deployment phase. These results are expected to be useful in designing the reliable brake system to control the deployment. In addition, small model experiment is employed to demonstrate the reliability of the present deployment method by using water rocket.

AAS 07 – 371

On-Orbit Jitter Measurement and Analysis of Precision Pointing Spacecraft and their Instruments

John Sudey, Jr., Nick Stamatakos, and Paul Kirchman, Swales Aerospace; Scott Miller, Orbital Science Corporation; Ken Yienger, NASA Goddard Space Flight Center

This paper presents jitter performance of the new generation of Geostationary Operational Environmental Satellite GOES-N spacecraft and instruments. Practical techniques are presented to demonstrate the importance of measuring and analyzing the dynamic interaction between the spacecraft and instruments for precision pointing spacecraft their Instruments. The discussion presented in this paper includes system requirements, mathematical modeling, 2D, FFT/3D/AFT, FFT image analysis, and instrument system sensitivity to jitter during ground and on-orbit testing. Methodology, techniques and sensors used to measure and subsequently optimize and compensate for the flight segment disturbance are also described.

AAS 07 – 372

Robustified Repetitive Controllers with Monotonic Convergence for Multiple-Input Multiple-Output Systems

Hunter M. Brown and Minh Q. Phan, Dartmouth College;
Soo Cheol Lee, Daegu University, Korea; Richard W. Longman, Columbia University

A method to design repetitive controllers with improved robustness for multiple-input multiple-output (MIMO) systems with uncertain parameters is presented. The parametric uncertainties are specified via their probability distribution functions. The controllers aim to produce monotonic convergence of all frequency components of the tracking errors from period to period. The method applies to any type of distribution functions specifying the uncertainties of any number of parameters. Robustification of the controllers is achieved by the multiple-model design principle.

SESSION 17: SPECIAL SESSION - STEREO
Chairs: Dr. Jose Guzman and Mr. Andrew Driesman
Johns Hopkins University Applied Physics Laboratory

AAS 07 – 373

STEREO Overview and History

Peter J. Sharer, Andrew Driesman, David W. Dunham and Jose J. Guzman,
The Johns Hopkins University Applied Physics Laboratory

STEREO (Solar TErestrial RElations Observatory) features a two-spacecraft formation in solar orbit. The work describes the development of the mission design concept for achieving the mission using lunar gravity assists. The design was successfully implemented following launch in October 2006. The spacecraft were placed into a leading-trailing formation with the Earth via lunar gravity in late-2006 and early 2007.

AAS 07 – 374

STEREO Launch Windows

Jose J. Guzman, Peter J. Sharer and David W. Dunham, The Johns Hopkins University Applied Physics Laboratory; Henry D. Friessen, United Launch Alliance

STEREO (Solar-TErestrial RElations Observatory) is the third mission in the Solar Terrestrial Probes program (STP) of the National Aeronautics and Space Administration (NASA). STEREO is the first mission to utilize phasing loops and multiple lunar flybys to alter the trajectories of more than one satellite. An overview and history of the program were presented in a previous paper. This paper will describe the launch computation methodology, the launch constraints, and the resulting nine detailed launch windows that were prepared for STEREO. More details will be provided for the window in late October 2006 that was actually used.

AAS 07 – 375

Withdrawn

AAS 07 – 376

STEREO Separation and ΔV Monte Carlo Analyses

Jose J. Guzmán, Peter J. Sharer and David W. Dunham,
The Johns Hopkins University Applied Physics Laboratory

STEREO (Solar-TErestrial RElations Observatory) is the third mission in the Solar Terrestrial Probes program (STP) of the National Aeronautics and Space Administration (NASA). STEREO is the first mission to utilize phasing loops and multiple lunar flybys to alter the trajectories of more than one satellite. An overview and history of the program, a description of the launch windows, and the actual launch were covered in previous papers. This paper will describe the pre-launch Monte Carlo runs performed to understand the impact of errors in the separation sequence and on the ΔV budget.

AAS 07 – 377

STEREO First Orbit and Early Operations

Daniel A. Ossing, David W. Dunham, Jose J. Guzmán, Gene A. Heyler and
John E. Eichstedt, The Johns Hopkins University Applied Physics Laboratory;
Henry D. Friessen, United Launch Alliance

This paper will describe STEREO's successful early operations during the first phasing orbit. This includes the autonomous detumble and solar array deployment after injection, and confirmation of spacecraft health and promotion to full operations. During the first orbit, both spacecraft performed two engineering ΔV maneuvers to calibrate and validate the propulsion system, which was also used for the 11.7 m/sec ΔV maneuver near apogee that raised perigee to prevent catastrophic atmospheric re-entry.

AAS 07 – 378

STEREO Maneuver Implementation

John W. Hunt, Jr., J. Courtney Ray, John E. Eichstedt and Hongxing S. Shapiro,
The Johns Hopkins University Applied Physics Laboratory

The orbit adjust maneuvers for each of the two STEREO (Solar-TErestrial RElations Observatory) spacecraft were designed to target lunar swingbys to insert the spacecraft into their respective heliocentric mission orbits. In this paper, we describe the spacecraft Guidance and Control system, the operations associated with testing and executing the desired maneuvers prescribed by the mission designers, the pre-maneuver analysis, and the maneuver execution and performance.

AAS 07 – 379

STEREO Phasing Orbits

David W. Dunham, Jose J. Guzmán and Peter J. Sharer, The Johns Hopkins University
Applied Physics Laboratory; Zane L. Nitskorski, University of Minnesota

This paper will describe the successful implementation (lunar swingby targeting) of the STEREO mission following the first phasing orbit to deployment into the heliocentric mission orbits following the two lunar swingbys.

SESSION 18: TRAJECTORY OPTIMIZATION - I
Chair: Dr. Craig McLaughlin, University of Kansas

AAS 07 – 380

Benefits of Adaptive Schemes for Trajectory Optimization

Luis Rodriguez, Benjamin Villac and Athanasios Sideris,
University of California, Irvine

This paper investigates the benefits of using adaptive schemes for the direct optimization of spacecraft trajectories by comparing two different algorithms, the first using a standard fixed time-step discretization, while the second a variable time-step approach. The algorithms are compared based on their performance on a set of low-thrust trajectory optimization problems and on several equivalent formulations of these problems in terms of various coordinates systems such as Cartesian, orbital elements and regularizing coordinates.

AAS 07 – 381

Computation of Boundary Controls Using a Gauss Pseudospectral Method

Geoffrey T. Huntington and David A. Benson, C. S. Draper Laboratory, Inc.;
Jonathan P. How, Massachusetts Institute of Technology;
Nicole Kanizay, Christopher Darby and Anil V. Rao, University of Florida

A computational approach is presented that improves the control approximation resulting from the Gauss pseudospectral transcription of an optimal control problem. The approach developed in this paper is a post-optimality computation where the Pontryagin minimum principle is applied at the boundaries to obtain a more accurate control approximation at the initial and final times. In particular, the approach uses both the boundary state (obtained from the primal solution of the nonlinear program) and the boundary costate (obtained via a previously developed costate mapping from the KKT multipliers of the nonlinear program). Three examples illustrate the improved control accuracy, and also show improved performance when the new control law is implemented in simulation. The results in this paper have the potential to be used in real-time.

AAS 07 – 382

Satellite Rendezvous Tours Using Multiobjective Evolutionary Optimization

Theodore R. Stodgell and David B. Spencer, The Pennsylvania State University

An autonomous spacecraft may one day face the task of rendezvousing with a set of targets sequentially under constraints such as timeliness, priority and ΔV cost. This type of rendezvous tour is reducible to a multiobjective wandering salesman problem (WSP) with dynamically moving vertices representing the rendezvous targets. Optimal tours are seen to minimize both the time taken to visit all targets and the total ΔV used. Evolutionary multiobjective optimization (EMOO) is well suited to this type of problem, handling mixed discrete and real-valued parameters in complicated environments. This research presents *Orbgnosis*, a satellite targeting and trajectory optimization tool that employs the Non-Dominated Sorting Genetic Algorithm II (NSGA-II).

AAS 07-383
Withdrawn

AAS 07 – 384

Optimal Strategies in Cooperative Games With Terminal Payoff

Rajnish Sharma, John E. Hurtado and Srinivas R. Vadali, Texas A&M University

A two pursuer, one evader capture game is studied. The focus of this paper is the establishment and investigation of a cooperation model among the pursuers, which allows capture to occur in a more efficient manner than if the pursuers did not cooperate.

AAS 07 – 385

Simulation on a Budget

Andrew Colombi, University of Illinois at Urbana-Champaign

A study, with focus on trajectory simulation, of next generation super computer technology is presented. Specifically, we utilize commodity Graphics Processing Units (GPUs) to calculate gravitational force using the polyhedral method and spherical harmonics. Experiments comparing speed and accuracy show a single GPU to be capable of outperforming a single conventional CPU by an order of magnitude.

AAS 07-386
Withdrawn

SESSION 19: SPACE DEBRIS AND CONJUNCTION ANALYSIS
Chair: Dr. Jeff Beck, Northrop Grumman Corporation

AAS 07 – 387

A First Order Forensic Analysis of China's Recent Anti-Satellite Test

Johannes M. Hacker, SpaceDev, Inc.

This paper will use the published NORAD two line element sets of the Fengyun 1 C debris cloud and propagate them backward to the engagement time. This propagation will use first order orbital perturbations due to Earth's gravitational field, and it will neglect atmospheric drag. Debris pieces that have significantly decayed in the atmosphere will be eliminated from this study. Using a delta-v "cloud" plotted in three dimensions in RIC coordinates and what is believed to be the Chinese launch site, this paper will attempt to make inferences about the original engagement geometry of the original ASAT test.

AAS 07 – 388

Uncertainty Characterization of Orbital Debris Using Simulated Space Surveillance Network Measurements

Jolanta Matusewicz and Kamesh Subbarao, University of Texas at Arlington;
Joe Frisbee, United Space Alliance

Orbit determination techniques are used to estimate the position and velocity of a debris object in orbit using range, azimuth, and elevation measurements obtained from Space Surveillance Network (SSN) sensors. Eight sensors from the SSN are simulated to track a debris object in an International Space Station (ISS) like orbit. Perturbations due to a 4 X 4 complex gravity model and an exponential atmospheric model are included in the two-body equations of motion that model the debris object in orbit. A nonlinear batch least squares technique is used to estimate the debris orbit. The position and velocity estimates are obtained for six sensor sites that were able to observe the debris object's orbit. Estimates are evaluated for a batch of 12 and 120 measurements.

AAS 07 – 389

Uncertainty Characterization of Orbital Debris Using the Extended Kalman Filter

Jolanta Matusewicz and Kamesh Subbarao, University of Texas at Arlington;
Joe Frisbee, United Space Alliance

Orbit determination techniques are used to estimate the position and velocity of a debris object in orbit using range, azimuth, and elevation measurements obtained from Space Surveillance Network (SSN) sensors. Eight sensors from the SSN are simulated to track a debris object in an International Space Station (ISS) like orbit. Perturbations due to a 4 X 4 complex gravity model and an exponential atmospheric model are included in the two-body equations of motion that model the debris object in orbit. The continuous-discrete Extended Kalman filter is used to estimate the debris orbit. The position and velocity estimates are obtained for six sensor sites that were able to observe the debris object orbit. Estimates are evaluated for a batch of 12 and 120 measurements.

AAS 07 – 390

Improvement of the Two-Line Element Accuracy Assessment Based on a Mixture of Gaussian Laws

Paul Legendre and Stéphanie Delavault, CNES, France;
Romain Garmier, G. Prat and Bruno Revelin, CS (Communication & System), France

In the framework of the experimental collision risk assessment led by CNES, an estimation of the accuracy of the TLE has been modeled based on a Gaussian law mixture. The goal of this study was to improve this error model in three different ways: first adapting the Expectation Maximization algorithm to handle the 3-D problem and to deal with "extreme measurements", then characterizing its temporal evolution, and finally defining object classes allowing to compute error models for newly catalogued objects. This paper will address the method in details, the results obtained and future ideas to improve the method.

AAS 07 – 391

Solar Radiation Pressure Estimation and Analysis of a GEO Class of High Area-to-Mass Ratio Debris Objects

Tom Kelecy, Boeing LTS; Tim Payne, Air Force Space Command; Robin Thurston, 1st Space Control Squadron; Gene Stansbery, NASA Johnson Space Center

A population of recently discovered deep space objects is thought to be high area-to-mass ratio (AMR) debris having origins from sources in the geosynchronous orbit (GEO) belt. The average AMR values have been observed to range anywhere from 1's to 10's of m^2/kg, and result in migration of eccentricity (0.1-0.6) and inclination over time. The nature of the debris dynamics also results time-varying solar radiation forces about the average which complicate the orbit process. The orbit determination results are presented for several of these debris objects, and highlight their unique and varied dynamic attributes.

AAS 07 – 392

SubVolumes in Dynamical Systems and the Tracking of Space Debris

J. M. Maruskin, D. J. Scheeres and A. M. Bloch, University of Michigan

Tracking and recognizing space debris has received much attention in recent years. Optical measurements can determine the angles and angular rates of a passing object, but the range and range-rate are left undetermined. The object's state is therefore constrained to exist in some two-dimensional surface in phase space. In addition to numerically integrating a sample of points in this surface, our work provides a quantitative way to determine area expansion and projection factors of local neighborhoods near any point on the uncertainty surface. This gives us additional structure and geometric insight into the spread of the probability distribution.

AAS 07 – 393

Beta Conjunction Analysis Tool

Salvatore Alfano, Center for Space Standards and Innovation

A means for assessing satellite conjunctions is presented. True and maximum probabilities are computed as well as the probability dilution threshold. A user-defined accuracy requirement is used to find the minimum relative velocity that ensures sufficient linearity. Nonlinear probability is computed by breaking the collision tube into sufficiently small cylinders. The first method does not account for gaps or overlaps of the abutting cylinders, the second eliminates these gaps and overlaps. The objects are treated as spheres for testing, but the complex nonlinear method is designed to handle any time-varying object shape.

AAS 07 – 394

Space Vehicle Conflict Probability for Ellipsoidal Conflict Volumes

Russell P. Patera, The Aerospace Corporation

This paper presents a method to compute conflict probability for ellipsoidal shaped conflict volumes. A coordinate system change and scale change are used to transform the elliptical conflict volume to a spherical conflict volume. The same transformations are used on the combined position error covariance, positions and velocities of the space objects. Once the transformations are made, the problem is that of finding the conflict probability for a spherical conflict volume. Conjunction statistics associated with three space collision events are used to evaluate the ability of ellipsoidal conflict volumes to identify high risk conjunction events.

SESSION 20: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL - II
Chair: Dr. Dennis Byrnes, Jet Propulsion Laboratory

AAS 07 – 395

GAME: Guidance with Avoidance During Maneuver Elaboration

Nicolas Théret, Jean-François Aubrun, Gérard Lassalle-Balier and Isabelle Sebbag, Centre National d'Etudes Spatiales (CNES), France;
Nicolas Descouvemont and Christian Delacroix, Ecole Nationale Supérieure de l'Aéronautique et de l'Espace (Supaéro), France

Some pieces of equipment of space-borne systems are sensitive to the light coming from celestial bodies. The problem of blinding will occur especially during attitude maneuvers, when the satellite moves out of the normal operating range. This problem is often solved by the conception of the space system, but constraints are then imposed on the mission. Another constraint-free strategy is to compute maneuvers that take account of forbidden zones avoidance. This is the purpose of the GAME method. The paper presents the method in detail, and gives some illustrated examples.

AAS 07 – 396

Innovative Nonlinear Predictive Control of Spacecraft Improved by Disturbance Observer

Frederic Claveau and Jean deLafontaine, Sherbrooke University, Canada

An innovative approach for the predictive control of spacecraft large-angle maneuvers is presented. This approach is based on the Nonlinear Generalised Predictive Control (NGPC) technique that minimizes the energy of the error on a prediction horizon. In view of the difficulty to obtain an analytical solution to the NGPC, taking into account the actuator saturation and the slew rate limit, a guidance law is designed to consider these limitations. A nonlinear disturbance observer is also used to enchance its disturbance rejection capability. Finally, simulations showing the results are presented in detail.

AAS 07 – 397

On the Implementation of Spacecraft Hovering Under Reduced-Order Dead-Band Control

Stephen B. Broschart, Jet Propulsion Laboratory;
Daniel J. Scheeres, University of Michigan

Hovering is a spacecraft station-keeping control scheme that uses thrust to directly counter the acceleration on the spacecraft. Hovering is a particularly attractive option for small-body missions because of the weak accelerations in that environment. A previous paper of ours showed that the zero-velocity surface that exists near a hovering spacecraft due to the Jacobi constant provides a restriction on the spacecraft motion that can be exploited using dead-band control. This paper explores that result further by looking at using typical measurement types as the basis of a dead-band control, the delta-V expense of hovering, numerically integrated hovering trajectories.

AAS 07 – 398

Singularity Avoidance of Control Moment Gyros Using Optimization of Initial Gimbal Angles and Application to Multi Target Pointing for Satellite Attitude Control

Yasuyuki Nanamori and Masaki Takahashi, Keio University, Japan;
Shigemune Taniwaki, Ehime University, Japan;
Kazuo Yoshida and Yoshiaki Ohkami, Keio University, Japan

Control Moment Gyros (CMG) has been expected to be applied to an earth observing satellite in recent years. However it is not easy to control it because CMG has a singularity condition and a major source of disturbance. Although there are many singularity avoidance logics, these use much resource of computer mounted on satellite. From the previous background, this paper presents a new but simple CMG steering law using preferred initial gimbal angles and null motion for high accurate attitude control system on an agile satellite. Preferred initial gimbal angles are decided by evaluating function considering inner state of CMG.

AAS 07 – 399

Preliminary Orbit Determination for Orbital Rendezvous Using Gauss' Method

Bryan E. Bingham and David K. Geller, Utah State University

In 1801 Carl Friedrich Gauss successfully determined the orbit of the planetoid Ceres using only angle measurements. In this paper, we will apply a modified version of Gauss' method to an orbital rendezvous navigation problem. Several rendezvous scenarios will be studied in which a chaser spacecraft with a known orbit attempts to determine the relative position and velocity of a target spacecraft with an unknown orbit. The chaser will make line-of-sight observations of the target and use these observations to determine the orbit of the target using Gauss' method.

AAS 07 – 400

Observability of Multi-Satellite Systems

Wei Kang and I. Michael Ross, Naval Postgraduate School;
Khanh Pham, Air Force Research Laboratory;
Qi Gong, University of Texas at San Antonio

In this paper we define and prove the observability of multi-satellite systems using relative measurements. In this work, GPS information is not required. This result on observability does not require any direct communication with the target to be detected. Therefore, it is applicable for both cooperative and non-cooperative targets. For multi-satellite systems with communication, the overall sensor payload required for observability can be reduced. Numerically checkable observability conditions are developed for multiple satellite systems connected by sensor and communication networks. To verify the theory, simulations using a UKF are carried out and they show good estimation accuracy.

AAS 07 – 401

The Road to Autonomous Orbital Rendezvous

David C. Woffinden and David K. Geller, Utah State University

Currently the majority of all the spaceflight experience in orbital rendezvous comes from the United States and Russian space programs. Both programs took two distinct approaches; the U.S. favored a more manual operation while the Russians pursued an automated methodology. This paper provides a comprehensive overview of the programs and missions that have come to define orbital rendezvous by highlighting the early rendezvous navigation systems and techniques in context of the rationale and events behind them, showing how they have matured to influenced ensuing programs, and explaining how the long standing traditional methods are converging toward autonomous orbital rendezvous.

AAS 07 – 402

Observability Criteria for Angles-Only Navigation

David C. Woffinden and David K. Geller, Utah State University

This paper presents a formal derivation of an analytical expression for the observability criteria for angles-only navigation. The solution, intended for orbital rendezvous applications, is also valid for any arbitrary linear dynamic system modeling the relative motion between two vehicles while measuring the relative LOS angles. An intuitive graphical interpretation is also provided along with several examples related to orbital rendezvous. From the basic ideas presented, they can be utilized to determine relative trajectories and maneuvers that optimize observability. In addition, they can be extended to determine the degree of detectability due to a selected rendezvous profile and sensor noise.

SESSION 21: SATELLITE CONSTELLATIONS AND FORMATION FLYING - III
Chair: Dr. Hanspeter Schaub, University of Colorado

AAS 07 – 403
A Decentralized Attitude Control for Spacecraft Formation Flying Via the State-Dependent Riccati Equation Technique

Insu Chang, Sang-Young Park and Kyu-Hong Choi, Yonsei University, Korea

The objective of this research is to present the decentralized coordinated attitude control using behavior-based control. The main contribution of this research is to introduce the State-Dependent Riccati Equation (SDRE) technique to the relative attitude control problem for spacecraft formation flying. We compare the effectiveness of controllers among PD, LQR and SDRE techniques in the system. In addition, we provide the numerical proof of local stability for the SDRE technique. In the practical sense, reaction wheels are applied to the simulation to control spacecraft attitude in the formation maneuver. Simulation results for attitude alignment demonstrate the effectiveness of SDRE approach.

AAS 07 – 404
Controlled Orbital Dynamics of Low Altitude Formations by Means of Electrical Propulsion

Giovanni B. Palmerini and Marco Sabatini, Sapienza Università di Roma, Italy;
Daniele Pavarin and Marco Manente, CISAS, Università di Padova, Italy

Design of performing formation flying control strategies depends on a correct representation of the actuators behavior. A complete closed loop control based on LQR approach, including uncertainties in state knowledge as well as thrust boundaries and foreseeable inaccuracies, is deeply investigated for a low altitude formation provided with electric propulsion. Main perturbations acting in LEO (J2 and drag) are considered, with test cases carried out at different altitudes. Performances for both an acquisition and a configuration-keeping phases are evaluated. Results of the complete model simulations are compared to the ones of simpler, computationally efficient models, to assess their reliability.

AAS 07 – 405

Optimal Multiple-Impulsive Reconfiguration Trajectories of Satellite Formation Flying

Dong-Yoon Kim, Sang-Young Park and Kyu-Hong Choi, Yonsei University, Korea; Byoungsam Woo, Space Systems/Loral

We investigate fuel-optimal formation reconfiguration trajectories using impulsive control. The formation reconfiguration is classified into three categories in this work: initialization, resizing, and reassignment. The reference orbit is considered as two-body circular orbit and Hill's equation is used to describe the formation orbit. A genetic algorithm as a global-optimization-tool is used to find sub-optimized two-impulsive trajectories. The primer vector technique as a local-optimization-technique is applied to fully search optimized solutions and to obtain multi-impulsive trajectories. The results show that fuel saving through multi-impulsive trajectory can be offered, however its amount is insignificant. Two-impulsive trajectories obtained by GA, therefore, are credible.

AAS 07 – 406

Model Predictive Control of Vehicle Formations

Jonathan S. Barlow and Minh Q. Phan, Dartmouth College

A method to design model predictive controllers for a group of vehicles is presented. It extends a previous result where the controllers minimize local cost functions associated with individual vehicles. Here a global receding-horizon cost function of the entire group is minimized. The controlled vehicles converge to pre-specified formation(s) and move together towards certain targets. The targets and the formations themselves can be time-varying. When full communication among all vehicles in the group is not possible, one can restrict communication of a vehicle to those in its neighborhood. A companion paper presents an adaptive version of the proposed controllers.

AAS 07 – 407

Adaptive Predictive Control of Vehicle Formations With Obstacle Avoidance

Jonathan S. Barlow and Minh Q. Phan, Dartmouth College

This paper presents an adaptive predictive control design for a group of vehicles to move in formations. Instead of identifying the vehicle predictive models from input-output data, and then designing the controller gains from the identified models, this paper presents a direct method where the controller gains are computed directly from the vehicle input-output data, bypassing the predictive model identification step. The adaptive version is useful because it allows the system to handle unexpected obstacles and changing operating environment. Numerical results are presented to illustrate the adaptive controller design method.

AAS 07 – 408
Withdrawn

AAS 07 – 409
Withdrawn

AAS 07 – 410
Flight Dynamics and Control of the JC2SAT Mission

Balaji Shankar Kumar and Alfred Ng, Canadian Space Agency, Canada;
Keisuke Yoshihara, Japan Aerospace Exploration Agency, Japan

The JC2SAT-FF mission will be the first mission ever to exercise close formation flying of two satellites with formation keeping and maneuvering solely with differential drag. From an operational point of view, the build-up and control of the JC2SAT formation poses various new requirements and challenges; the safe injection of the two spacecraft together from the launcher, the safe separation of the two spacecraft from the stacked configuration, a collision-free drift of the spacecraft to the required position and the formation keeping of the spacecraft at the desired position. This paper will provide details of the flight dynamics and a brief discussion of the control laws that will help the mission reach its objectives.

SESSION 22: TRAJECTORY OPTIMIZATION - II
Chair: Dr. Todd Cerven, The Aerospace Corporation

AAS 07 – 411
A Series Solution Method for the Solution of the Hamilton Jacobi Isaacs Equation and its Applications to Aerospace Systems

Rajnish Sharma, John E. Hurtado and Srinivas R. Vadali, Texas A&M University

A novel application of the series solution approach for terminally constrained nonlinear optimal control problems is proposed for solving the time dependent Hamilton Jacobi Isaacs (HJI) equation. The HJI equation appears in nonlinear pursuit-evasion games and designing H-infinity control laws. As the first innovative application of the proposed methodology to solving the HJI equation, this paper considers the example of nonlinear differential games in orbits. The HJI equation is solved in order to construct nonlinear feedback strategies for finite time pursuit and evasion scenarios involving space assets. A soft terminal constraint is used to penalize terminal error. The second novel application presented in the paper is associated with finite-time H-infinity control formulation for hard constrained optimal control problems with disturbances. Several examples are illustrated.

AAS 07 – 412

Optimal Nonlinear Feedback Controller Design Using a Waypoint Scheme

Rajnish Sharma, Srinivas R. Vadali and John E. Hurtado, Texas A&M University

This paper discusses an innovative idea of blending the notion of a waypoint scheme with a series solution method of solving the Hamilton Jacobi Bellman Equation developed by the authors for designing the optimal nonlinear feedback control laws for analytic terminally constrained systems. The paper begins with the theoretical aspects of the algorithm followed by some key derivations. The overall time interval of the given problem is partitioned into smaller pieces and the series solution method is applied within each piece with the use of stored gains computed for one time interval only. The methodology is applied to highly nonlinear examples including minimum fuel orbit transfer problem. Several examples are demonstrated and compared with the open-loop solution to demonstrate the efficacy of the proposed method.

AAS 07 – 413
Presented in Session 10

AAS 07 – 414

Optimal Earth Escape Using Soyuz Launches from Kourou

Jose Manuel Sánchez Pérez, GMV S.A. at ESA/ESOC, Germany

An alternative escape strategy using the Soyuz-Fregat 2-1b mid-size launcher vehicle from the European spaceport at Kourou has been designed to maximize the payload mass into interplanetary trajectories. Instead of a direct escape launch, the spacecraft is inserted onto an inclined highly eccentric Earth orbit and a sequence of manoeuvres at the perigee performed by the on-board propulsion unit allows reaching the required escape conditions. This paper describes the methodology and results obtained during the mission analysis studies of this strategy, which may be applied to the next generation of European exploration missions such as ExoMars.

AAS 07 – 415
Withdrawn

AAS 07 – 416

Improved Orbit Transfer Switching Function Analysis by an Extended Frequency Study

Brian Jamison and Victoria Coverstone, University of Illinois at Urbana-Champaign

Previous analysis of the switching function (SF) for minimal propellant trajectories has provided useful criteria for the optimization process. Also, former work has yielded analytical equations for the co-states during coasting, allowing for an analytical expression for the SF during coasting arcs. Recent work used an analytical solution to determine the maximum frequency of the SF during coasting. Such an analysis can rapidly provide appropriate bounds for a zero-finding algorithm (ZFA). This paper reviews several ZFAs and a comparison of speed in convergence to zeros of the SF is provided for a range of orbit transfers.

SESSION 23: ORBITAL DYNAMICS, PERTURBATIONS AND STABILITY

Chair: Dr. David Spencer, Pennsylvania State University

AAS 07 – 417

Correct Modeling of the Indirect Term for Third Body Perturbations

Matthew M. Berry and Vincent T. Coppola, Analytical Graphics, Inc.

The indirect term in the formula for third body perturbations models the acceleration of the primary body due to the third body. This term is necessary because the integration frame, which has its origin at the center of the primary body, is not inertial. The term is normally computed analytically, assuming both bodies are point masses and only gravitational forces affect the primary body. However, these assumptions lead to inaccuracies when other forces act on the primary body. Computing the indirect term numerically, using finite differencing to find the acceleration of the primary body, can reduce those inaccuracies.

AAS 07 – 418

Withdrawn

AAS 07 – 419

Withdrawn

AAS 07 – 420

Third-Body Perturbation in the Case of Elliptic Orbits for the Disturbing Body

Rita de Cássia Domingos and Rodolpho Vilhena de Moraes, UNESP/FEG, Brazil;
Antonio Fernando Bertachini de Almeida Prado, DEM/INPE, Brazil

A semi-analytical and a numerical study are presented for the perturbations caused in the motion of a spacecraft by a disturbing body. A double averaged analytical model is used. The disturbing function is expanded in Legendre polynomials up to the fourth-order. The theory developed is used to study the behavior of a spacecraft, where the Moon is the disturbing body. A set of numerical simulations is performed for the evolution of the mean orbital elements for a long time period considering different initial eccentricities for the satellite and spacecraft. Several plots show the time-histories of the Keplerian.

AAS 07 – 421

Stability Analysis of the Attitude of Artificial Satellites Subject to Gravity Gradient Torque

Rodolpho Vilhena de Moraes, UNESP/FEG, Brazil;
Regina Elaine Santos Cabette, DEM/INPE, Brazil;
Maria Cecília Zanardi, UNESP/FEG, Brazil;
Teresinha J. Stuchi, IF/UFRJ, Brazil

Using a canonical formulation and considering gravity gradient torque the stability of the rotational motion of artificial satellites is analyzed. Here, the variables describing the rotational motion are the Andoyer's variables. The approach used in this paper requires the reduction of the Hamiltonian to a normal form. Equilibrium points are found and using generalized coordinates the Hamiltonian is expanded in the neighborhood of these points. Using Lie-Hori theory the Hamiltonian is normalized up to order four. Simulations are done considering data sets for hypothetical satellites with characteristics similar to the SCD Brazilian satellites and the American satellite PEGASUS.

AAS 07 – 422
Withdrawn

AAS 07 – 423

Earth Satellite Orbits as KAM Tori

William E. Wiesel, Air Force Institute of Technology

Kolmogorov, Arnold, and Moser predicted that trajectories in lightly perturbed Hamiltonian systems should lie on tori, now known as KAM tori. In this paper we show that this appears to be the case for most, if not virtually all earth orbits perturbed by the entire geopotential. Methods for determining the torus frequencies and coordinate Fourier series are developed and their accuracy is evaluated.

SESSION 24: EARTH ORBITAL AND PLANETARY MISSION STUDIES
Chair: Dr. David Geller, Utah State University

AAS 07 – 424

Optimal Path Planning for Spacecraft Formation Flying: Planning Architecture and Operations

Ross Burgon, Jennifer A. Roberts and Peter C. E. Roberts,
Cranfield University, United Kingdom

A number of future space missions are being planned to exploit the unique dynamical and environmental locality of the Sun-Earth collinear libration points, in particular the L2 point. Of these missions, the use of formation flying of distributed space systems (DSS) is receiving much attention especially for space-based interferometry. Architectures for the autonomous planning of optimal spacecraft trajectories are presented incorporating five defined optimisation modules that can generate collision-free, fuel-optimal trajectories about L2 for interferometry manoeuvres. The first of these modules, the operations planner, is introduced and a tool developed (for use onboard) that is able to optimally schedule mission observations significantly better than a simple benchmark.

AAS 07 – 425

Optimal Visitation Order for Spacecraft Servicing Missions

Brian J. Wadsley and Robert G. Melton, Pennsylvania State University

The problem of visiting a set of satellites for servicing (repair/refueling) can be formulated as a Wandering Salesman Problem (unconstrained start and end points). Other researchers have shown that for closely neighboring orbital planes, the problem is simplified by examining the orbital angular momenta projected onto a common plane. This paper approaches the problem using a dynamic programming algorithm and addresses situations where perturbations have significant effect across the lifetime of the mission, and/or the orbital planes have substantially different inclinations.

AAS 07 – 426

Potential for Tsunami Detection and Early-Warning Using Space-Based Passive Microwave Radiometry

Rebecca G. Myers, Massachusetts Institute of Technology;
John E. Draim, Aerospace Consultant;
Paul J. Cefola, Consultant in Aerospace Systems, Spaceflight Mechanics/Astrodynamics

The threat of a tsunami in coastal communities is considerable, especially in the Pacific and Indian Oceans. Presently, detection relies on bottom-pressure recorders at single point locations and tide gauge data close to shorelines, limiting reaction time. The ability to detect a tsunami in the deep ocean is being proposed using space-based passive microwave radiometry. Passive microwave radiometry can detect parameters such as sea-surface temperature and sea roughness to contribute to earlier detection, farther from shore, to increase the reaction time for coastal communities at risk.

AAS 07 – 427

On the Fundamental Frequencies of Satellite Relative Motion and Control of Formations

S. R. Vadali, P. Sengupta, H. Yan and K. T. Alfriend, Texas A&M University

In this paper, we examine the behavior of J2 perturbed relative orbits. We study the in-plane and out-of-plane relationships as a function of the orbit inclination. It has been observed by way of numerical simulations by others that for certain special values of the inclination, the relative orbits do not precess for a significant period of time. This paper presents an analysis of the problem and provides a clear reason for this enigmatic behavior.

AAS 07 – 428

Understaning Maneuver Uncertainties During Inclination Maneuvers of the Aqua Spacecraft

David P. McKinley, a.i. Solutions, Inc.

During the Fall 2006 inclination campaign for the Aqua spacecraft it was discovered that there was significant uncertainty in the prediction of the Semi-Major Axis change during a maneuver. The low atmospheric drag environment at the time of the maneuvers amplified the effects of this uncertainty leading to a potential violation of the spacecraft ground-track requirements. In order to understand the uncertainty, a Monte Carlo simulation was developed to characterize the expected Semi-Major Axis change uncertainty given the observed behavior of the spacecraft propulsion and attitude control systems during a maneuver. This expected uncertainty was then used to develop new analysis tools to ensure that future inclination maneuver plans will meet ground-track control requirements in the presence of the error.

AAS 07 – 429

Stardust Earth Return Orbit Determination

Darren T. Baird, Moriba Jah, David Jefferson, Brian Kennedy, George Lewis, Tomas Martin-Mur, Tim McElrath, Neil Mottinger, Sumita Nandi and Paul F. Thompson, Jet Propulsion Laboratory

The delivery of the Stardust spacecraft to the landing site at the Utah Test and Training Range (UTTR) on January 15, 2006 was the culmination of a seven-year mission. During the last two months of the mission, three Trajectory Correction Maneuvers were executed to steer the spacecraft toward the target. Complications to the orbit prediction process were encountered because of frequent thruster firings and solar radiation pressure. Insights obtained from these studies were folded into a baseline filter strategy, which evolved as the spacecraft dynamics became better understood. These efforts and the operations results are described in the paper.

AAS 07 – 430

Free Flying External Occulter Mission Design, Simulation, and Analysis

Ian J. E. Jordan, Computer Sciences Corporation

This presentation will encompass mission design, computer simulations, and analysis of free-flying external occulter space astronomy missions with emphasis on traverse modelling of a likely range of ES-L2 terrestrial planet finder (TPF) class vehicles. A theoretical model relating critical mission parameters will be contrasted with computer simulation. The model constraints will be discussed in context of meeting critical science criteria for completeness of surveys around target stars. Discussion of the model implementation to single and multiple occulters and its extensibility to future applications will be highlighted.

SPECIAL LECTURE

AAS 07 – 431

Space: Journeying Toward the Future (Abstract Only)

Dr. Roger D. Launius, AIAA Distinguished Lecturer;
Division of Space History, Smithsonian Institution National Air and Space Museum

In the fifty years since the beginning of the space age in 1957, much has been accomplished, our knowledge advanced, and a future made more positive. This presentation offers a survey of spaceflight history and offers comments on what might be expected in the next fifty years. It focuses on five major challenges in spaceflight for the twenty-first century: (1) political will to continue aggressive space exploration, (2) inexpensive, reliable space access, (3) smart robotic explorers, (4) protecting this planet and this species from space, and (5) human exploration of the Moon and Mars.

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