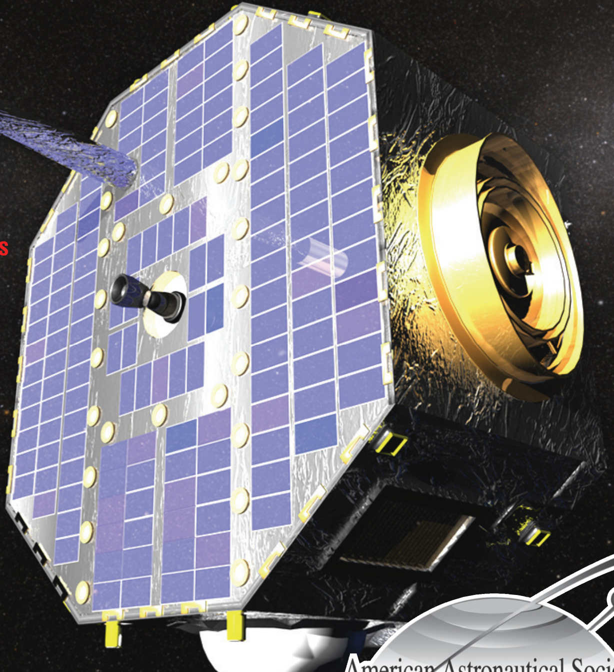
SPACEFLIGHT MECHANICS 2009



Edited by
Alan M. Segerman
Peter C. Lai
Matthew P. Wilkins
Mark E. Pittelkau

American Astronautical Society

CD-ROM Supplement to Volume 134
ADVANCES IN THE ASTRONAUTICAL SCIENCES

SPACEFLIGHT MECHANICS 2009

Front Cover Illustration:

An artist's impression of the Interstellar Boundary Explorer (IBEX) spacecraft exploring the edge of our solar system. This is the first NASA spacecraft to image and map the dynamic interactions taking place where the hot solar wind slams into the cold expanse of space (Image Credit: Walt Feimer, NASA Goddard Space Flight Center).

American Astronautical Society

SPACEFLIGHT MECHANICS 2009

Volume 134

ADVANCES IN THE ASTRONAUTICAL SCIENCES

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FOREWORD

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

Spaceflight Mechanics 2009, Volume 134, *Advances in the Astronautical Sciences*, consists of three parts totaling about 2,500 pages, plus a CD ROM supplement which contains all the available papers in digital format. Papers which were not available for publication are listed on the divider pages of each section in the hard copy volume. A chronological index and an author index are appended to the third part of the volume.

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

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

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

AAS/AIAA SPACEFLIGHT MECHANICS VOLUMES

Spaceflight Mechanics 2009 appears as Volume 134, *Advances in the Astronautical Sciences*. This publication presents the complete proceedings of the AAS/AIAA Space Flight Mechanics Meeting Conference 2009.

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

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

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

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

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

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

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

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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*).

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

AAS/AIAA ASTRODYNAMICS VOLUMES

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Robert H. Jacobs, Series Editor

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 19th Annual Space Flight Mechanics Meeting was held from February 9 through February 12, 2009, in Savannah, Georgia at the Hilton Savannah DeSoto Hotel. The meeting was sponsored by the American Astronautical Society (AAS) Space Flight Mechanics Committee and co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. Approximately 176 people registered for the meeting. Attendees included engineers, scientists, and mathematicians representing government agencies, the military services, industry, and academia from the United States and abroad.

There were 142 technical papers presented in 22 sessions on topics related to space flight mechanics and astrodynamics. An excellent plenary speech titled "Industry's Obligation for Mission Success" was given by Dr. Alexander C. Liang of The Aerospace Corporation on Tuesday afternoon. Note that Dr. Liang unfortunately passed away on May 2, 2009, due to stroke. The two special sessions on Interstellar Boundary Explorer (IBEX) and Advanced Attitude Control Sensors were well received and strongly attended. A special workshop on Advanced Sciences and Technology Research Institute for Astrodynamics (ASTRIA) was held on Thursday by Dr. Moriba Jah of the Air Force Research Laboratory (AFRL).

The meeting included four social events. The Early-Bird Reception was held in the Telfair Art Museum on Sunday evening. On Monday evening, the 2009 AAS Dirk Brouwer Award recipient, Dr. Bob Schutz, presented his lecture entitled "From Geodesy to Satellite Geodesy." On Tuesday evening, attendees enjoyed a beautiful Savannah riverboat cruise, where the evening ended with many attendees winning exotic souvenirs in a lottery drawing. A Student and Young Professional Reception was sponsored by the Georgia Institute of Technology, Guggenheim School of Aerospace Engineering on Wednesday evening.

The editors extend their gratitude to the Session Chairs who made this meeting successful: Angela Bowes, Dennis Byrnes, John Carrico, Dr. William Cerven, Dr. Michael Gabor, Dr. James Gearhart, Bob Glover, Dr. Yanping Guo, Dr. Felix Hoots, Dr. Moriba Jah, Dr. Brian Kawauchi, Dr. Thomas Lovell, Dr. Don Mackison, Dr. Ryan Park, Dr. Chris Ranieri, Dr. Ryan Russell, Dr. Hanspeter Schaub, Dr. Paul Schumacher, Dr. Tom Starchville, Dr. Aaron Trask, Dr. James Turner, and Dr. Kenneth Williams. Our gratitude also goes to Dr. Shannon Coffey for his support and assistance with website admin- istration.

We would also like to express our thanks to Schafer Corporation for the program cover design and printing of the conference programs, and for donated supplies.

Dr. Alan M. Segerman
AT&T Government Solutions, Inc.
AAS Technical Chair

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

Dr. Matthew P. Wilkins
Schafer Corporation
AAS General Chair

Dr. Mark E. Pittelkau
Aerospace Control Systems
Engineering and Research, LLC
AIAA General Chair

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ADVANCES IN THE ASTRONAUTICAL SCIENCES, SPACEFLIGHT MECHANICS 2009 (2009)

(AAS/AIAA Space Flight Mechanics Meeting, February 8-12, 2009, Savannah, Georgia)

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Chair: Bob Glover, AT&T

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Withdrawn

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Withdrawn

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Algorithm of Automatic Detection and Analysis of Non-Evolutionary Changes in Orbital Motion of Geocentric Objects

Sergey Kamensky,* Andrey Tuchin,* Victor Stepanyants* and Kyle T. Alfriend†
* "Vympel" Corporation, Moscow, Russia.
† Dept. of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA.

The goal of this work is the development of methods and algorithms for the automatic detection and analysis of non-evolutionary changes in orbital motion of geocentric objects caused by maneuvers and other events (but not by natural perturbations). The task is formulated for three kinds of non-evolutionary changes, namely the single impulse maneuver, two impulses maneuver and small continuous thrust. The methods and algorithms are developed. Examples of the algorithm work are given.

AAS 09 – 104

Deriving Density Estimates using Champ Precision Orbit Data for Periods of High Solar Activity

Andrew Hiatt, Craig A. McLaughlin and Travis Lechtenberg
Department of Aerospace Engineering, University of Kansas, Lawrence, Kansas 66045, USA.

Atmospheric density modeling is one of the greatest uncertainties in the dynamics of satellites in low Earth orbit. Accurate density calculations are required to generate meaningful estimates of the atmospheric drag perturbing satellite motion. This paper utilizes precision orbit data from the Challenging Minisatellite Payload (CHAMP) satellite as measurements in an optimal orbit determination process to generate density estimates during periods of increased solar activity. The results are compared with CHAMP accelerometer derived density for determining the accuracy of the density estimates derived from precision orbit data. The density and ballistic coefficient Gauss Markov process half-lives and baseline density model were changed in a systematic fashion to obtain the results. The results were correlated to the accelerometer derived densities for each solution and organized into solar and geomagnetic activity bins and in an overall summary. Using the cross correlation coefficients provides a quantitative means by which to choose the best baseline density model and Gauss Markov half-life combination for use in an optimal orbit determination scheme. The precision orbit derived densities show higher correlation to the accelerometer derived densities than the Jacchia 1971 empirical density model.

AAS 09 – 105

Geosat Follow-on Precision Orbit Improvement through Drag Model Update

Stephen R. Mance,* Craig A. McLaughlin,* Frank G. Lemoine,† David D. Rowlands,† and Paul J. Cefola‡

* Department of Aerospace Engineering, University of Kansas, Lawrence, Kansas 66045, USA.

† Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771, USA.

‡ Consultant in Aerospace Systems, Spaceflight Mechanics, and Astrodynamics; Sudbury, Massachusetts, USA.

The NRLMSISE-00 density model and density corrections found using the dynamic calibration of the atmosphere process were implemented in GEODYN, the NASA GSFC Precision Orbit Determination and Geodetic Parameter Estimation Program. These updates are used in an attempt to improve the orbit precision of GEOSAT Follow-on (GFO). The corrections used in this paper apply to altitudes up to 600 km. Since GFO is in an 800 km orbit, these corrections pave the way for a future addition of density corrections which will be in the appropriate altitude regime. The updates made to GEODYN were compared through SLR residuals, orbit overlaps between adjacent arcs, and changes in the empirical accelerations. The comparisons show little change from the original MSIS-86 density routine regardless of solar and geomagnetic activity level.

AAS 09 – 106

On Preliminary Orbit Determination: A New Approach

Reza Raymond Karimi and Daniele Mortari

Dept. of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA.

A new approach for preliminary orbit determination based on angles-only observations is presented. The proposed technique is iterative and uses the Lagrangian coefficients f and g which is similar to the Gauss' method of orbit determination from this aspect. As opposed to the Gauss' approach, the method is not singular for the coplanar case. The proposed technique is finally compared with the classic iterative method of Double-r. The presented technique is also capable of handling multiple observations for higher accuracy whereas the level of the algorithm complexity remains the same as opposed to the available methods. Also the data were corrupted with noise to simulate the true measurements. Results show our method as a valid alternative to the classical methods of orbit determination.

AAS 09 – 107

Comparision of Different Methods of LEO Satellite Orbit Determination for a Single Pass Through a Radar

Zakhary N. Khutorovsky,* Sergey Yu. Kamensky,* Nickolay N. Sbytov,*
Kyle T. Alfriend†
* "Vympel" Corporation, Moscow, Russia.
† Dept. of Aerospace Engineering, Texas A&M University, College Station, Texas 77843-3141, USA.

The primary approaches used for orbit determination on the basis of a single pass through a radar are recursive (Kalman filter) and joint (least squares). If the stochastic characteristics of the errors are not completely known or the measurement errors are time correlated these techniques do not provide a guaranteed evaluation of the errors of the generated estimates. This is a significant limitation. This paper presents a comparative analysis (based on computer simulation) for the procedures based on the Guarantee method and traditional recurrent and joint processing techniques.

AAS 09 – 108

Passive Multi-Target Tracking with Application to Orbit Determination for Geosynchronous Objects

Kyle J. DeMars* and Moriba Jah†
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†Air Force Maui Optical and Supercomputing Site, AFRL, Kihei, Hawaii 96753, USA.

As telescope systems achieve greater photometric sensitivity and metric accuracy, the number of detected and tracked objects in deep space orbits around the Earth is likely to increase exponentially. The Pan-STARRS 1 (PS1) telescope, just now coming on line atop Mount Haleakala on the Island of Maui (at the Maui Space Surveillance System [MSSS]), will provide 19-22 visual magnitude sensitivity and sub arc-second metric accuracy for track-mode sensitive objects. The PS1 system is being funded and developed collaboratively by the University of Hawaii Institute for Astronomy and the Air Force Research Laboratory (AFRL). One of the goals is to determine a Concept of Operations (CONOPS) that accommodates the expected density of objects that will be detected, primarily in the Geosynchronous Orbit (GEO) regime. The challenge is to adopt a survey and tracking scheme that does the best job of processing the data that are collected (both astrometry and photometry) for all of the detected objects in a given set of frames to produce estimated and predicted orbits. The analysis presented here is limited to objects likely to be detected in the GEO orbit regime by PS1. A method is presented herein which combines Set-Hypothesis Tracking along with a Probability Data Association Filter in order to associate observed objects with existing tracks as well as initiate objects which are being observed for the first time. The results from this implementation are encouraging and if successful could be used in a near real-time, autonomous implementation.

SESSION 2: RENDEZVOUS, RELATIVE MOTION, FORMATION FLIGHT, AND SATELLITE CONSTELLATIONS 1
Chair: Dr. Aaron Trask, Apogee Integration

AAS 09 – 109
A Cooperative Egalitarian Peer-to-Peer Strategy for Refueling Satellites in Circular Constellations

Atri Dutta and Panagiotis Tsiotras

D. Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0150, USA.

We address the problem of peer-to-peer (P2P) refueling of satellites in a circular constellation. In particular, we propose a Cooperative Egalitarian P2P (CEP2P) strategy that combines the ideas of Cooperative and Egalitarian P2P refueling strategies introduced in our previous work. During a CE-P2P maneuver, a fuel-sufficient satellite and a fuel-deficient satellite engage in a cooperative rendezvous, exchange fuel, and then return to any available orbital slots left vacant by other active satellites. We propose a methodology, based on a network flow formulation, to determine the CE-P2P maneuvers that use the minimum amount of fuel during the ensuing orbital transfers. Since the methodologymay yield sub-optimal solutions, we provide estimates of sub-optimality of these solutions. Finally, and with the help of numerical examples, we compare the CE-P2P, E-P2P and C-P2P alternatives, and demonstrate the benefits of CE-P2P maneuvers in terms of reducing the overall fuel expenditure.

AAS 09 – 110
An Investigation of Teardrop Relative Orbits for Circular and Elliptical Chief Satellites

David J. Irvin Jr.,* Richard G. Cobb† and T. Alan Lovell‡

* Space Based Infrared Systems Wing, U.S. Air Force.

† Dept. of Aeronautics & Astronautics, Wright-Patterson Air Force Base, Ohio 45433, USA.

‡ U.S. Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, New Mexico 87117, USA.

Relative satellite motion between a chief and deputy satellite that are in close vicinity is well described by the Clohessy-Wiltshire (CW) equations which in more general form can accommodate chiefs in eccentric orbits. When the chief and deputy satellites have different periods, the resulting relative orbit drifts in the chief-fixed reference frame. Under most conditions these drifting relative orbits produce teardrop formations in which the trajectory intersects itself in the chief's orbit plane, providing an opportunity for the deputy to thrust and remain on the teardrop. These formations have been explored extensively for chiefs in circular orbits. The research presented herein expands the teardrop concept to elliptical chief orbits and seeks to find fuel-optimal trajectories for long term "hovering" in the vicinity of the chief.

AAS 09 – 111

Control System Design and Simulation of Spacecraft Formations Via Leader-Follower Approach

Mahmut Reyhanoglu

Physical Sciences Dept., Embry-Riddle Aeronautical University, Daytona Beach, Florida 32114, USA.

This paper presents an effective leader-follower based control scheme for spacecraft formations. Modifying earlier established control design techniques, passivity-based feedback laws are constructed to control translational and rotational motion of a group of spacecraft. Computer simulations are carried out to illustrate the effectiveness of the control laws. The ephemeris and attitude data generated through the simulations are used to create 3D visualizations.

AAS 09 – 112

Decentralized Optimization for Control of Satellite Imaging Formations in Complex Regimes

Lindsay D. Millard and Kathleen C. Howell

School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, 47907, USA.

Decentralized control and agent-based modeling techniques are employed to determine optimal spacecraft motion for formations having multifaceted objectives in complex dynamic regimes. Cooperative satellite "agents" share a common objective (high resolution imaging) and simultaneously pursue private goals (minimal fuel usage). An algorithm is developed based on dual decomposition. The solution from an agent-based model is compared to a traditional, non-linear optimal control solution. Then, by exploiting the reduced computational requirements, the agent-based model simulates arrays with increasing numbers of satellites and constraints.

AAS 09 – 113

Electromagnetic Flat Docking System for in-Orbit Self-Assembly of Small Spacecraft

Samia Smail and Craig I. Underwood

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A novel method of in-orbit assembly of small Intelligent Self-powered Modules (ISMs) is presented. This is achieved using the Electromagnetic Flat Docking System (EFDS). Compared with conventional docking mechanisms, the EFDS is a propellantless docking adapter, designed to control the motion of the ISMs during the final approach procedures. With its simple sensors and actuators, plume impingement is mitigated and precise alignment is not needed prior to initial contact. This paper mainly focuses on the design of the electromagnets that serve as a means of guiding two ISMs from a separation distance of 10 meters up to physical coupling.

AAS 09 – 114

Investigations of a Massive, Non-Spherical Chief in Close Proximity Formations

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A method is devised to provide orbit control of the elements of a small spacecraft formation using the highly non-spherical gravitational potential of a nearby, co-orbiting massive body, such as a rocket body, at the formation center. The baseline motion of the formation elements is described by the well-known Hill-Clohessy-Wiltshire equations, and the perturbing effect of the large mass at the center of the Hill's frame is highly dependent on the chief's attitude. This dependence provides a means of controlling the positions of the formation elements, and some methods for implementing that control are investigated.

AAS 09 – 115

One-Dimensional Testbed for Coulomb Controlled Spacecraft

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This paper discusses the preliminary results of a novel testbed developed to examine relative motion of craft using electrostatic or Coulomb forces. The Coulomb Formation Flight (CFF) concept uses active charge emission to control the naturally occurring spacecraft potential in space to maintain desired separation distances. These forces are on the order of milli-Newtons and can strongly influence relative motion of geostationary satellites dozens of meters apart. Simulating such charged relative motion in a terrestrial environment is very challenging. The testbed consists of a non-conducting one-dimensional hover track which can levitate a charged craft. With a secondary charged object and the ability to change the potential it is possible to actuate the suspended craft and study the relative motion due to charge. The challenges of developing this first generation electrostatic actuation testbed are outlined, including the mechanics of constructing the hover track, sensing the position of the cart, limiting the airflow supply as well as designing and implementing the cart which carries an electrostatic charge. Gravity disturbances are characterized and presented with test run data as well as preliminary results demonstrating that the Coulomb testbed successfully achieves electrostatic relative motion actuation.

SESSION 3: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL 1
Chair: Dr. James Turner, TAMU Aerospace Engineering

AAS 09 – 116

Spacecraft Constellation Orbit Estimation Via a Novel Wireless Positioning System

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In formation flying, it is important for all spacecraft to sustain their orbit. The orbit can be maintained if the absolute position of spacecraft can be estimated. This paper introduces a novel Wireless Local Positioning System (WLPS) that can be used to keep the absolute positions of spacecraft in formation flying. The WLPS enables one spacecraft to locate other spacecraft's relative position. Two scenarios that are two spacecraft and three spacecraft configurations are considered. Simulations are conducted to investigate the potential of Extended Kalman Filter (EKF) to estimate the relative position of spacecraft and incorporate it to maintain the absolute position of the spacecraft. The EKF stability using WLPS-only measurement is compared to the case when we also take into account the measurements taken by a radar system installed on the earth capable of localizing at least one spacecraft. The average root mean square error (RMSE) performances of different scenarios are compared and the impact of parameters such as the mean relative distance and the mean altitude is investigated.

AAS 09 – 117

A New Optimal Orbit Control for Two-Point Boundary-Value Problem Using Generating Functions

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The optimal control problem of a spacecraft using impulsive and continuous thrust where the terminal state and time interval are explicitly given is considered. Using a recently developed technique based on Hamilton-Jacobi theory, we develop a method to approximate the solution of the Hamilton-Jacobi equation which can solve the two-point boundary-value problem. The proposed method is based on the successive approximation and Galerkin spectral method with Chebyshev polynomials. This approach is expected to derive the analytical solution of the optimal control problem in the large domain. Numerical simulation is given to illustrate the theory.

AAS 09 – 118

Improvement of Vision-Based Estimation Using Multiple Vector Observations

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Multiple (three or more) line-of-sight vector observations are used to improve relative attitude and position estimation performance for a pair of spacecraft preparing to rendezvous. Multiple LOS vector observations are generated by strategically arraying beacons on the chief spacecraft. An observability analysis of the six-degree-of-freedom attitude and position determination problem is used to verify the effectiveness of the beacon configurations. An extended Kalman filter is used for the state estimation. In order to evaluate simulation results, the norms of the attitude and position errors are numerically integrated over thirty minutes of the final approach rendezvous phase.

AAS 09 – 119

Optimal Guidance for Lunar Ascent

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The objectives of this paper are (a) to review the analytical solution for the minimum-time rocket transfer with constant thrust in a plane over a flat moon and (b) to use it in a sample and hold optimal guidance scheme for orbital insertion. The general solution of the minimum-time problem is derived. Next, it is used to compute the minimum-time trajectory from the surface of the moon to orbital insertion. Then, in optimal guidance, this solution process is used at each sample point to compute a new optimal control, and it is held constant over the sample period. Finally, flat moon guidance is adapted to a spherical moon.

AAS 09 – 120

Desensitizing the Minimum-Fuel Powered Descent for Mars Pinpoint Landing

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Desensitized Optimal Control (DOC) methodology is applied to the problem of minimum fuel powered descent on Mars, in order to reduce the landing errors in the presence of uncertainties and perturbations. Unlike the conventional practice of designing separately the nominal trajectory and a feedback tracking controller, DOC strategy incorporates the two designs in synergy, delivering better tracking performance. Within this study, a point mass model with a uniform gravitational field is used, with the engine throttle being the control variable which is bounded between two non-zero settings. Most dominating perturbations during the powered descent stage are considered, including the initial deliver errors of the position and velocity, mid-course position update errors, and the uncertainties on the engine thrust. Linear Quadratic Regulator (LQR) technique is used to design the feedback control gains. In order to reduce the likelihood of the closed loop throttle exceeding the prescribed bounds, a multiplicative factor is applied to the feedback gains. In the meantime, sensitivities of the final position and velocity with respect to state perturbations at all times are derived, and augmented onto the minimum fuel performance index through penalty factors. As a result, the nominal trajectory is reshaped from the well-known maximum-minimum-maximum profile with little extra fuel consumption such that the nominal throttle is encouraged to stay away from the bounds. Monte-Carlo simulations show that the occurrence of out of bound throttles are significantly reduced, resulting in improved landing precision. LQR technique is also used to design feedback control laws to guide the lander to a different target detected during the descent, and Monte Carlo simulations are performed to verify the performance of the algorithm.

AAS 09 – 121

Finite Set Control Transcription for Optimal Control Applications

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Previous efforts explore an enhanced collocation method designed to treat optimal control applications in which control variables are constrained to finite sets of values. Presently, the method is applied to several aerospace control problems to demonstrate its utility and capability. On-off actuation schemes are ideally represented with constrained control. The behavior of variable-thrust actuators is modeled by limiting control change rates to a finite space. Solutions derived are characterized as optimal switching schedules between feasible control values. The methodology allows control switches to be determined over a continuous spectrum, overcoming many of the limitations associated with discretized solutions.

AAS 09 – 122

Autonomous Optical Lunar Navigation

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The performance of optical autonomous navigation is investigated for spacecraft in low lunar orbits and highly elliptical lunar orbits. Various options for employing the camera measurements are presented and compared. Strategies for improving navigation performance are developed and applied to the Orion vehicle lunar mission.

AAS 09 – 123

Rigid Body Inertia Estimation with Applications to the Capture of a Tumbling Satellite

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A framework for rigid-body inertia estimation is presented which is general and may be used for any rigid body undergoing either torque-free or non-torque-free motion. It is applied here to the case of a tumbling satellite. Included are a geometric interpretation of the estimation problem which provides an intuitive understanding of when to expect good estimation results and simulation results to demonstrate the viability of the method.

SESSION 4: ATTITUDE SENSING, ESTIMATION, AND CALIBRATION 1
Chair: Kenneth Williams, KinetX, Inc.

AAS 09 – 124
Partial Disk Tracking Using Visual Snakes: Application to Spacecraft Pose Estimation

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The ability to accurately estimate the position and orientation of one object with respect to another lies at the heart of many ground, air and space operations. To this affect, this paper investigates a vision based strategy to solve the relative pose problem by tracking four independent spheres whose relative geometry is known. The novel aspect is that the sphere outlines do not need to be complete to compute a solution. Rather, target segments are used to estimate the true apparent sphere center and radius. The vision sensor used is a camera. The camera is fixed to the object whose pose is to be calculated relative to the spheres. It is assumed that the position and orientation of the camera frame with respect to the object frame to which it is attached, is known. The vision sensor is equipped with active deformable contour algorithms (visual snakes), the outputs of which are used in the proposed pose estimation algorithm. Compared to earlier work which looked at calculating the relative pose based line of sight measurements only, this paper also looks at incorporating depth estimates into the algorithm, which can lead to an improved solution. The proposed method allows for a unique solution with only three spheres, as opposed to four which is the minimum needed if only line of sight measurements are used.

AAS 09 – 125
Fast Access and Low Memory Star Pair Catalog for Star Identification

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Star pattern identification-based attitude determination has resulted in development of numerous methods relating to star information databases. At Boeing, given an autonomous Lost-in-Space method based on identification of star pairs, we require a star pair catalog (database with specified star pairs) as well as a standard star catalog (database with information on individual stars). In this paper, we discuss the catalogs' architecture, size optimization, methods for catalog generation, and methods for on-board autonomous updating of the catalogs. We compare our catalogs' structures with other published structures and illustrate by simulated results.

AAS 09 – 126

The K-Vector ND and its Application to Building a Non-Dimensional Star Identification Catalog

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A multi-dimensional orthogonal range-searching algorithm (K-Vector ND) is presented. The algorithm is analyzed and found to have an execution time that is independent of the size of that database, for well-distributed data sets. Numerical tests are performed to determine the performance advantage as compared to a Quad-Tree for the two-dimensional data set. Results range from break-even to a factor of 14, depending on the database size. The K-Vector ND is then applied to the problem of building a non-dimensional star-identification database that contains all visible star triples. The performance of the K-Vector ND algorithm in that task is then compared to a simple nested loop, and found to range from break-even to a factor of 200, depending on the size of the database.

AAS 09 – 127

Performance of Spin-Axis Attitude Estimation Algorithms With Real Data

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The paper presents the application of the Tanygin-Shuster (T-S) algorithm for spin-axis attitude determination. The sensor data originate from two satellites with different orbit and attitude characteristics. The most appropriate data intervals are identified using criteria based on measurement sensitivities. A minimum-variance technique is formulated for establishing the Earth aspect angle from the measured chord angles. The attitude determination results are affected by measurement biases. The chain of covariance transformations from the fundamental sensor measurement errors to the final attitude error is presented. The unit-vector normalization, which is inherent in the T-S method, is beneficial for the stability of the attitude determination results under biases for both satellites.

AAS 09 – 128

Time Tag Issues in the Star Tracker and Gyro Data for ICESat Precision Attitude Determination

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We describe several time tag problems for ICESat's star trackers and gyros. Problems include star tracker time tag shifts for one or more orbital periods, periodic spikes in the gyro rate, compressed gyro data, and a gyro time tag bias. We discuss possible causes for each problem, the effects on ICESat attitude determination and pointing determination, and methods to handle the problems and meet mission requirements.

AAS 09 – 129

Using Quantum Search Algorithm in Future Spacecraft Attitude Determination

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In this paper we study the potential application of quantum search algorithm to the spacecraft navigation with focus on attitude determination. Traditionally the attitude and orbit determination can be achieved by recognizing the relative position/attitude to the background stars using sun sensors, earth limb sensors, or star trackers. Due to the massive celestial database, however, star pattern recognition is a complicated and power consuming job. We propose a new method of attitude and orbit determinations by applying the quantum search algorithm to the search of a specific star or star pattern. The quantum search algorithm, proposed by Grover in 1996, could search the specific data out of an unstructured database containing a number of N data in only $O(\sqrt{N})$ steps, while it would take conventional computers to look through an average of N/2 steps. As a result, by taking the advantage of matching a particular star in a vast celestial database in very limited steps, we could acquire the position/attitude of the spacecraft rapidly for navigation, guidance and control.

AAS 09 – 130

Nonsingular Attitude Filtering Using Modified Rodrigues Parameters

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A method to estimate the general rigid body attitude using a minimal Modified Rodrigues Parameters (MRP) coordinate set is presented. The singularity avoidance technique is based on the stereographic projection properties of the MRP set, and makes use of a simple mapping relationship between MRP representations. Previous work has used the MRP duality to avoid singular attitude descriptions but has ignored the associated covariance transformation. This paper presents a mapping to transform the state covariance matrix between these two representations as the attitude description is mapped between the two possible MRP sets. Second–order covariance transformations suitable for divided difference filtering are also provided. The MRP filter formulation based on extended Kalman filtering and divided is compared with a standard multiplicative quaternion Kalman filter in an example problem.

SESSION 5: IBEX SPECIAL SESSION
Chair: John Carrico, Applied Defense Solutions

AAS 09 – 131

Mission Design for the Interstellar boundary Explorer (IBEX) Mission

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The Interstellar Boundary Explorer mission was successfully launched on October 19th, 2008. This mission was achieved with a small octagonal spacecraft, launched on a Pegasus rocket. The IBEX spacecraft is a sun-pointed spinner with 2 narrow angle FOV sensors specialized to detect neutral atoms from the solar system's outer boundaries and galactic medium. IBEX used a STAR-27 solid rocket motor and its own onboard propulsion system to boost itself into a high altitude cislunar orbit. The orbit achieved is a high eccentricity orbit, approximately 48 Re apogee by 20,000 Km radius perigee. The authors describe the orbit, attitude, operational, and hardware selections used to meet the science objectives.

AAS 09 – 132

Prelaunch Trajectory Design and Analysis for the IBEX Mission

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The Interstellar Boundary Explorer mission was successfully launched on October 19th, 2008. In this paper the authors describe the trajectory design and analysis that enabled IBEX to meet its science objectives. The authors give details on the ascent profiles used to transfer from the initial orbit to the final orbit with flexibility to account for launch dispersions. The orbit modeling and targeting methodologies used to plan the two-year baseline orbit are presented, including the techniques to control the unstable nature of the highly elliptical 8-day period cislunar orbit. Details of the launch window analysis, station-keeping plans, and collision avoidance analysis are also presented.

AAS 09 – 133

Prelaunch Orbit Determination Design and Analysis for the IBEX Mission

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The Interstellar Boundary Explorer mission was successfully launched on October 19th, 2008. This paper describes the prelaunch analysis performed to enable real-time orbit accuracy to meet mission requirements. The results of simulations of various measurement types and schedules are presented. These simulations included the ascent maneuver models and uncertainty in performance. The authors also present how real observations from other spacecraft were used to characterize the tracking plans prior to launch. Details are given on the analysis for the launch and early orbit phase as well as the nominal operations.

AAS 09 – 134

Trajectory Design Operations for the IBEX Mission

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The Interstellar Boundary Explorer mission was successfully launched on October 19th, 2008. The authors present the techniques used in operations to plan the trajectory ascent accounting for launch and maneuver dispersions. The authors give the results of maneuver planning and calibration, and reconstruction of the launch and solid rocket motor firing. The models and algorithms used to plan the multiple-maneuver phasing loop ascent are described, as well as details of how the final mission orbit was achieved. The authors present how Monte Carlo analysis was used in operations to ensure that the science objectives would be met over the two-year mission lifetime.

AAS 09 – 135

Orbit Determination Operations for the Interstellar Boundary Explorer

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The Interstellar Boundary Explorer (IBEX) successfully launched on October 19, 2008. The orbit determination techniques applied proved to be effective and met the unique needs of the highly elliptical IBEX trajectory. During the early operations phase of this mission, particular orbit estimation challenges were addressed including orbit raising phasing loops, the maneuvers involved, and in modeling the tracking system, its uncertainties, and biases, while meeting the real-time operational schedule. In addition, the real-time position and velocity covariance estimate was directly applied operationally. In this paper, the orbit determination processes from launch through routine operations are fully described and the results are presented.

AAS 09 – 136

Effect of IBEX Spinning Attitude on Doppler Observations

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The primary observation type for orbit determination for the IBEX spacecraft is ground based two-way Doppler. During early operations, IBEX was spinning at 22 to 60 RPM. The antenna used for taking Doppler observations is offset from the spacecraft spin axis which resulted in a high frequency oscillation in the Doppler data that was orders of magnitude larger than the noise level of the observations. A low pass filter was designed to remove the high frequency content from the Doppler signature. The modified observations were validated via simulation prior to application of the technique to the real tracking data.

SESSION 6: ORBIT DYNAMICS 1
Chair: Dr. James Gearhart, Orbital Sciences Corporation

AAS 09 – 137

A Cubed Sphere Gravity Model for Fast Orbit Propagation

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The cubed sphere model of the gravity field maps the primary body to the surface of a segmented cube, with a basis defined on the cube surface for interpolation purposes. As a result, the model decreases orbit propagation time and provides a localized gravity model. This paper provides a brief description of the cubed sphere model, which is currently derived from the spherical harmonics. Early tests of the integration constant did not meet requirements, thus the model was reconfigured to improve accuracy. A detailed characterization of the model was then performed to profile agreement with the base model. The new model closely approximates the spherical harmonics with orbits deviating by a fraction of a millimeter at or above feasible Earth-centered altitudes.

AAS 09 – 138

A Nonsingular Approach in Satellite Theory

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Nonsingular differential equations for the variation of variables suggested by Lagrange for the motion of an artificial satellite under the influence of the Earth gravitational field are developed keeping the usual orbital elements. It is shown that no singularities are present in these equations except for the case of a retrograde equatorial orbit. Equations are developed for secular, long period and short period perturbations. The advantage of retaining the usual orbital elements is to avoid a complex and cumbersome form of the equations.

AAS 09 – 139

Analytic Construction of Periodic Orbits in the Circular Restricted Three Body Problem With Small Mass Parameter

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Analytical solutions for three body motion are sparse in the literature but still sought for many reasons. In this paper, an analytic solution for motion of the third body in a circular orbit in the plane of motion of the two primaries is introduced, for small mass parameter and when the motion is in the vicinity of one of the two primaries. In this case, the Jacobi function allows implementation of Legendre polynomials, and the Jacobi integral equation is reduced to the Legendre normal form of an elliptic integral. A closed form expression for the period of motion is formulated and expressions for coordinates as functions of time are also introduced. The speed of the third body is found to be nonuniform along the path. The obtained solution gives insights into the physics of the three body problem. This solution can be used as a generating orbit for purposes of numerical or analytical continuation of periodic orbits in three body systems in which mass parameter is close but not equal to zero.

AAS 09 – 140

Bézier Representation of Analytical Functions

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This paper provides a methodology to optimally approximate analytical functions with non-rational and rational Bézier curves. The great flexibility of Bézier curves is here highlighted by direct comparison with Padé rational approximation of analytical functions and other methods where appropriate. Current results show a non-questionable superiority of Bézier rational approximation with respect to Padé representations. There are several potential applications of the proposed theory (e.g., in optimal control) which will follow in subsequent papers. In general, wherever Padé approximation is adopted to approximate analytical functions, it can be substituted by Bézier representations.

AAS 09 – 141

Nearly Circular Equatorial Orbits of a Satellite About an Oblate Body With Atmosphere

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This paper studies nearly circular equatorial orbits of satellites in the gravitational field of an oblate body that includes the J_2 term and Quadratic drag. We derive analytic expressions for the orbit of a satellite under these conditions even if the local atmospheric density is provided in tabular form. This work includes four distinct atmospheric density models. A closed-form solution of the orbit equation for each model is compared with the numerical integration of the exact orbit equation disclosing the accuracy of the analytic solution that follows from each model. The simulations reveal some highly accurate results.

AAS 09 – 142

PPKBZ9^{A,SA} Two Orbit Propagators Based on an Analytical Theory

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In the context of general perturbation theories, we analyze the motion of an artificial satellite around an Earth-like planet perturbed by the first eight zonal harmonic coefficients. By means of two Lie trasforms and the Krylov-Bogoliubov-Mitropolsky method we produce a closed-form second-order analytical theory. Except for the critical inclination, this theory is valid for small eccentricities and inclinations. Two orbit propagators are derived from the analytical theory. The first one, PPKBZ9^{A}, is completely analytical while the second one, PPKBZ9^{SA}, is based on numerical methods that compute the transformation of the variables. Prediction accuracy given by the orbit propagator programs is investigated by using data of different types of Earth and Mars orbiters. PPKBZ9^{A} can be also used by means of a friendly Web Interface in *Astrody(Web/Tools)* Web Site.

AAS 09 – 143

Evolution Strategies for Computing Periodic Orbits

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An evolution strategy algorithm belonging to the general field of genetic algorithms is developed to detect periodic orbits in dynamical problems. The algorithm is applied to the problem of motion of a particle under the gravitational field of a solid circular wire.

SESSION 7: LOW THRUST MISSION AND TRAJECTORY DESIGN
Chair: Dr. Ryan Russell, Georgia Institute of Technology

AAS 09 – 145
An Efficient Method for Computing Near-Optimal, Low-Thrust Earth-Orbit Transfers

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A new low-thrust trajectory optimization tool has been developed. This method can quickly obtain minimum-time, three-dimensional Earth-orbit transfers, and can accommodate Earth-shadow effects. Two key features improve the computational speed and convergence properties of the optimization technique: (1) the use of a simple, iterative scheme for generating a good initial guess for the trajectory-shaping parameters, and (2) the use of a simplified Earth-shadow model. An iterative initial-guess generator improves a preliminary set of trajectory-shaping parameters that are based on Edelbaum's classic analytic method (and extensions to Edelbaum's original work) for optimizing quasicircular transfers. The subsequent parameter optimization problem involves a small set of free optimization variables (less than ten), and the numerical search rapidly converges to an optimal solution. Several numerical trials demonstrate the accuracy and run-time performance of the new optimization method. This preliminary analysis suggests that the new efficient optimization method would be a useful tool for mission and spacecraft designers.

AAS 09 – 146
Applications of Constraint Stabilization to Low-Thrust Mission Design

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The design and analysis of low-thrust transfers in a mission design context generally involves several tasks, such as preliminary design and trade-studies in low- or medium-fidelity models, optimization into a high-fidelity model and the design of a navigation and guidance scheme. While optimal control has proved to be an effective tool to address these issues, the complementary use of suboptimal methods for the first two tasks, such as shape-based methods or Q-laws, accelerates the design process that ultimately converge toward a satisfying nominal design. In this paper, we propose a close-loop reformulation and an extension of shape-based methods in the setting of constraint stabilization methods to provide a simple and effective tool to address the transformation of a low-fidelity design into a higher fidelity model and the design of a guidance law. This generalization also provides further flexibility in applying shape-based methods for the preliminary design tasks. The method is demonstrated in the case of transfers between circular orbits bound to the Earth.

AAS 09 – 147

Design Concept and Modeling of an Advanced Solar Photon Thruster

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The so-called “compound solar sail”, also known as “Solar Photon Thruster” (SPT), holds the potential of providing significant performance advantages over the flat solar sail. Previous SPT design concepts, however, do not consider shadowing effects and multiple reflections of highly concentrated solar radiation that would inevitably destroy the gossamer sail film. In this paper, we propose a novel advanced SPT (ASPT) design concept that does not suffer from these oversimplifications. We present the equations that describe the thrust force acting on such a sail system and compare its performance with respect to the conventional flat solar sail.

AAS 09 – 148

Design of Optimal Low-Thrust Lunar Pole-Sitter Missions

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Using a thruster similar to Deep Space 1’s NSTAR, pole-sitting low-thrust trajectories are discovered in the vicinity of the L_1 and L_2 libration points. The trajectories are computed with a seventh-degree Gauss-Lobatto collocation scheme that automatically positions thrusting and coasting arcs, and aligns the thruster as necessary to satisfy the problem constraints. The trajectories appear to lie on slightly deformed surfaces corresponding to the L_1 and L_2 halo orbit families. A collocation scheme is also developed that first incorporates spiraling out from low-Earth orbit, and finally spiraling down to a stable lunar orbit for continued uncontrolled surveillance of the lunar south pole. Using direct transcription, the pole-sitting coverage time is maximized to 554.18 days, and the minimum elevation angle associated with the optimal trajectory is 13:0°.

AAS 09 – 149

Withdrawn

AAS 09 – 150

Low-Thrust Control of Lunar Orbits

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A method is presented for the control of lunar orbiters using continuous low-thrust propulsion. While the proposed approach is fairly general and could be useful for a variety of mission scenarios, in this work it is applied to the particular case of obtaining a lunar Sun-synchronous orbit for use in a lunar mapping mission. Using optimal control theory, it is shown that a lunar orbit can be obtained that is low-altitude, near-polar, and Sun-synchronous. The analysis of the optimal control problem leads to the commonly seen two-point boundary value problem, which is solved using an indirect shooting algorithm.

AAS 09 – 151

Multiobjective Optimization of Low-Thrust Trajectories Using a Genetic Algorithm Hybrid

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In low-thrust, gravity-assist trajectory design, two objectives are often equally important: maximization of final spacecraft mass and minimization of time-of-flight. Generally, these objectives are coupled and competing. Designing the trajectory that is best-suited for a mission typically requires a compromise between the objectives. However, optimizing even a single objective in the complex design space of low-thrust, gravity-assist trajectories is difficult. The technique in this development hybridizes a multi-objective genetic algorithm (NSGA-II) and an efficient, calculus-based direct method (GALLOP). The hybrid algorithm capitalizes on the benefits of both methods to generate a representation of the Pareto front of near-globally optimal solutions.

AAS 09 – 152

Trajectory to the Orbit Largely Inclined with the Ecliptic Plane by Way of Electric Propulsion Delta-V Earth Gravity Assist

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The study on the post-HINODE Solar Observation Mission has been started by members in the Solar physics community. One candidate of the mission targets on the observation of the high latitude region of the Sun, which requires the injection of the space observatory (spacecraft) into the orbit largely inclined with the ecliptic plane. Reported in this paper are the trajectory design results for this orbit transfer, which contains a sequential application of the Electric Propulsion Delta-V Earth Gravity Assist (EDVEGA) procedure.

SESSION 8: ORBIT DYNAMICS 2
Chair: Dr. Felix Hoots, The Aerospace Corporation

AAS 09 – 153
Displaced Periodic Orbits with Low-Thrust Propulsion in the Earth-Moon System

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Solar sailing and solar electric technology provide alternative forms of spacecraft propulsion. These propulsion systems can enable exciting new space-science mission concepts such as solar system exploration and deep space observation. The aim of this work is to investigate new families of highly non-Keplerian orbits, within the frame of the Earth-Moon circular restricted three-body problem (CRTBP), where the third massless body utilizes a hybrid of solar sail and a solar electric thruster. The augmented thrust acceleration is applied to ensure a constant displacement periodic orbit above L_2, leading to simpler tracking from the lunar surface for communication applications. Using an approximate, first order analytical solution to the nonlinear non-autonomous ordinary differential equations, periodic orbits can be derived that are displaced above/below the plane of the CRTBP.

AAS 09 – 154
Fast Orbit Propagation Without Solving Kepler's Equation

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A predictor-corrector approach is used for orbit propagation without solving Kepler's equation. The value of the eccentric anomaly is estimated under a constant time interval constraint by linear or quadratic approximations and then corrected using a single Newton-Raphson or Halley iteration. Numerical tests show that the quadratic propagation with the Halley correction has an accuracy comparable with the machine error for the elliptic and hyperbolic cases. Two very accurate approaches pushing elliptical and hyperbolic formulations to near parabolic (e.g. e = 0:99999), have been developed. The proposed method has constant complexity (it is not iterative), does not require precomputed data, and can be implemented in just two lines of code.

AAS 09 – 155

Gravitational Potential of a Massive Disk

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This article studies the main features of the dynamics around a massive annular disk. The first part addresses the difficulties finding an appropriated expression of the gravitational potential of a massive disk, which will be used later on to define the differential equations of motion of our dynamical system, and for the algorithms computing families of periodic orbits. The second part of the article describes the dynamics of a particle orbiting around a massive annular disk by means of a description of the main families of periodic orbits, their bifurcations and linear stability.

AAS 09 – 156

Identification of Non-Chaotic Terminator Orbits Near 6489 Golevka

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Terminator orbits are an attractive class of quasi-periodic orbits for missions to small bodies because they exhibit stable behavior in the presence of a strong solar radiation pressure perturbation and robustness against uncertainty in the gravitational environment. Here, a numerical procedure is demonstrated for extracting long-term stability characteristics of terminator orbit dynamics. This approach yields a quantitative description of the region in state space that results in long-term stable terminator orbit dynamics in a high-fidelity dynamical model. These *body-specific* results complement the more generalized analytical results by providing more detail on the orbit stability properties in a particular situation of interest and stability information when the implicit assumptions of the analytical results do not apply.

The procedure first identifies periodic orbits in the augmented Hill problem numerically, then evaluates the long-term behavior of nearby initial conditions using the Fast Lyapunov Indicator of chaoticity in a high-fidelity dynamical model that includes solar radiation pressure, an elliptical heliocentric small-body orbit, and a irregular rotating small-body gravity field. The procedure is successfully demonstrated on a model of the asteroid 6489 Golevka and results are compared with existing analytical results. This approach also has application to the study of orbiting particles and moons.

AAS 09 – 157

Lunar Analytical Theory for Polar Orbits in a 50-Degree Zonal Model

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Low-altitude orbiters about the moon require full potential fields for accurate modeling. Therefore, analytical theories are usually discarded in the preliminary mission design of close lunar orbiters for the huge formal expressions that need to be handled. However, specific applications allow for certain reduction. This is the case of polar orbits, where a rearrangement of the perturbing function makes it possible to carry out dramatic simplifications that allow us to cope with fifty zonal harmonics analytically. The theory reflects the real long-term behavior of low-altitude, polar, lunar orbiters and may be useful in preliminary mission design.

AAS 09 – 158

Computation and Applications of an Orbital Dynamics Symplectic State Transition Matrix

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This paper presents a numerical method for deriving a symplectic state transition matrix for an arbitrary Hamiltonian dynamical system. It provides the exact solution space mapping of the linearized Hamiltonian systems, preserving the symplectic structure that all Hamiltonian systems should possess by nature. The symplectic state transition matrix can be applied to accurate, yet computationally efficient dynamic filters, long-term propagations of the motions of formation flying spacecraft and the eigenstructure/manifold analysis of N-body dynamics etc., when the exact structure-preserving property is crucial. We present the derivation and key characteristics of the symplectic state transition matrix, and apply it to the two-body dynamics, circular restricted three-body problem and to an Earth orbit with perturbation forces based on the real ephemeris. These numerical examples reveal that this numerical symplectic state transition matrix shows improvements in preserving the structural properties of the state transition matrix as compared with the conventional linear state transition matrix with Euler or Runge-Kutta integrations.

AAS 09 – 159

The IAU 2000A and IAU 2006 Precession-Nutation Theories and Their Implementation

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The IAU 2000A precession-nutation theory relates the International Celestial Reference Frame to the International Terrestrial Reference Frame and has been effective since January 2003. In 2006, the IAU moved to adopt a more dynamically consistent precession model to complement the IAU 2000A nutation theory. This update – described as IAU 2006 precession in the 2009 Astronomical Almanac – is effective January 2009. Now there are multiple numerical standards relating the ICRF and ITRF precise to within a few ìas. In this paper, the impact of alternative (yet acceptable) ITRF-to-ICRF transformations is discussed, and an operational alternative is also proposed that is computationally faster and easier to maintain, while preserving precision.

SESSION 9: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL 2
Chair: Dr. Moriba Jah, Air Force Research Laboratory

AAS 09 – 160

Designing an Interplanetary Autonomous Spacecraft Navigation System Using Visible Planets

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Duality exists between the problem of orbit determination from line-of-sight measurements and the problem of designing an interplanetary autonomous navigation system. While the first problem estimates the observed body orbit using the observer orbit knowledge, the second problem does exactly the opposite. However, in an interplanetary navigation problem, in addition to the measurement noise we need to consider (1) the *light-time effect* due to the finite value of the speed light and (2) the *aberration of light* (also referred to as the astronomical aberration), which has been here considered by including also the contribution given by the restricted (special) relativity. These two effects require modification of the classic orbit estimation problem. This paper shows how to extend orbit determination methods of Gauss and the technique developed by the current authors [1] (a Gauss-based technique) when observing distant planets. The results show that the accuracy provided by our technique is higher than those provided by Gauss' method.

AAS 09 – 161

Withdrawn

AAS 09 – 162

Optimal Autonomous Orbit Control Of Remote Sensing Spacecraft

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This paper analyses the problem of the autonomous control of a satellite in Low Earth Orbit (LEO) using an optimum controller. The type of controller considered is a standard Linear Quadratic Regulator (LQR). As the problem can also be treated as a two-satellites-formation control in which there is no cancellation of the common perturbative forces, its formulation is similar to that used in formation flying control problems. The driving orbit control requirement is to keep the satellite orbit within a maximum absolute distance of 250 m (r.m.s.) from a sun-synchronous, phased and frozen reference orbit. The control action is realized by means of in-plane and out of-plane thrusts whose cost is minimized by the optimal solution of the control problem. The PRISMA dual satellite mission flight software development and test environment is used as a first test-bed to validate the control algorithms. The PRISMA flight software and test environment allows a very realistic validation of the proposed control techniques. The TerraSAR-X mission scenario is used as a second test-bed for the validation of the control algorithm as it is a very representative example of LEO satellite for Earth observation with high demanding orbit control accuracy requirements.

AAS 09 – 163

Orbit Determination Covariance Analysis for the Cassini Extended Mission

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The accurate navigation of the prime Cassini tour around Saturn has resulted in excess propellant on board the spacecraft. This will allow further exploration of Saturn and its satellites. In order to ensure the success of an extended mission, all aspects of the tour navigation have to be planned in advance. This paper describes the results of a covariance study that was undertaken to assess the navigational capabilities for the extended tour from an orbit determination point of view, to estimate pointing accuracies at all the flybys for science planning, and to establish a ΔV budget for the maneuvers needed to keep the spacecraft on the reference trajectory.

AAS 09 – 164

Pseudospectral Optimal Control Algorithm for Real-Time Trajectory Planning

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We present the development and implementation of a new pseudospectral (PS) optimal control-based algorithm for autonomous trajectory planning and control of an Unmanned Ground Vehicle (UGV) with real-time information updates. The basic algorithm is presented and used to solve a dynamic trajectory planning problem. The UGV mission is to traverse from an initial start point and reach the target point in minimum time, with maximum robustness, while avoiding both static and dynamic obstacles. This is achieved by deriving the control solution that carries out the initial planning problem while minimizing a cost and satisfying constraints based on the initial global knowledge of the area. The control solution is repeatedly recomputed and updated throughout the vehicle's mission. To combat the problem of inaccurate global knowledge and/or a dynamic environment, the UGV uses its sensors to map the locally detected changes in the environment and continuously updates its global map before re-computing the next control solution that can achieve an optimal trajectory to the goal. We present the complete algorithm and its successful implementation through various scenarios.

AAS 09 – 165
Withdrawn

AAS 09 – 166

Vision-Based Relative State Estimation Using the Unscented Kalman Filter

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This paper presents a new approach to spacecraft relative attitude estimation and navigation based on the unscented Kalman filter which was implemented and evaluated for rendezvous and proximity operations. The use of the unscented Kalman filter requires propagation of carefully selected sigma points from the nonlinear system to map probability distribution more accurately than is possible using the linearization of the standard extended Kalman filter. This approach leads to faster convergence when using inaccurate initial conditions in attitude estimation and navigation problems. This method uses observations from a vision sensor to provide multiple line of sight vectors from the chief spacecraft to the deputy spacecraft. Because the observation equations associated with the vision sensor are coupled with the attitude matrix and the relative position vector, the estimation is performed based on the initial attitude and the initial navigation information. A multiplicative quaternion error is derived from the local attitude error that guarantees that the quaternion unit constraint is maintained in the filter. One scenario chosen for the study was the simulation of bounded relative motion for 10 hours, and another scenario chosen was a 30-minute rendezvous maneuver. Simulation results show that, in these scenarios, the unscented Kalman filter is more robust than the extended Kalman filter under realistic initial attitude and navigation conditions. The relative navigation results are validated by comparing them with the relative orbit computed by the High Precision Orbit Propagator (HPOP) of Satellite Tool Kit (STK). Finally, the estimation of the rendezvous maneuver is shown by comparing with the reference trajectory, a linear impulse rendezvous based on a Cochran-Lee-Jo (CLJ) transition matrix for an elliptical orbit.

SESSION 10: ATTITUDE DYNAMICS AND CONTROL 1
Chair: Dr. Hanspeter Schaub, University of Colorado

AAS 09 – 168
Pointing Performance Investigation of a Multiple Rigid Body Spacecraft

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Earth Observation (EO) missions are characterized by high pointing performance. Also, spacecraft payloads are becoming more capable, demanding more power (and solar array area). This additional array area including its structural flexibilities has to be taken into account in the modeling of satellite dynamics, as well as disturbances and the components of attitude control system. A modeling task is undertaken to accurately represent the satellite and its components in the simulation environment. The pointing performance metrics are defined and implemented in the simulation loop as a part of this task. The effect of solar array configuration on the pointing performance is investigated.

AAS 09 – 169
Attitude Control by Magnetic Torquer

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One of the most effective ways for performing low-cost attitude control of satellites is by utilizing the Earth's magnetic-field. In this paper, we present attitude control techniques that use only magnetic devices for active control. First, we summarize a few methods that have been used in orbit. Next, we discuss the details of the control methods. As a concrete example, we select a 50-kg class university satellite, which has three-axis magnetic torquers as the main control equipment. In addition, it has an extension boom that helps attitude stabilization by means of the gravity-gradient effect. We divide the operation period into three main phases corresponding to the expected attitude conditions. We construct a few effective attitude control methods and evaluate control performances on the basis of the results of detailed simulations. Finally, we present details of the development and calibration of magnetic torquers.

AAS 09 – 170

Development of Control and Measurement System for the Three-Dimensional Reaction Wheel

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This paper presents a development of an attitude control device called three-dimensional reaction wheel. This device consists of only one levitated spherical rotor which can rotate around arbitrary axes without mechanical contact between the stator. This leads to the reduction of the weight and space of the device, and the failure caused by the mechanical contact would be also reduced. To develop this system, it is required to measure 3-DOF rotation of spherical rotor with a contactless method. In this paper, a new method measuring three-axes angular velocity of spherical rotor is proposed. Using this method, rotation control of a spherical rotor is evaluated experimentally.

AAS 09 – 171

Use of Taylor Expansions of the Inverse Model to Design FIR Repetitive Controllers

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Slight imbalance in rotating parts on spacecraft can produce vibrations that compromise the operation of fine pointing equipment. Repetitive control (RC) applied on an isolation mount can in theory completely eliminate the influence of such periodic disturbances. A very effective RC design method based on optimization in the frequency domain was presented previously. It develops compensators that exhibited specific patterns of zero locations. This paper takes a different time domain approach and develops an RC design method based on Taylor series expansions of the reciprocals of zero factors in the system transfer function. The approach is very simple, straightforward, and easy to use. It also supplies considerable insight, and gives understanding of the cause of the patterns for zero locations. The approach forms a different and effective time domain design method, and it can also be used to guide the choice of parameters in performing the frequency domain optimization design.

SESSION 11: MISSION DESIGN 1
Chair: Dennis Byrnes, Jet Propulsion Laboratory

AAS 09 – 172

Maneuver Plans for the First ATV Mission

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On 03/09/2008, the first ESA Automated Transfer Vehicle (ATV), so-called Jules Verne, lifted off from Kourou aboard the Ariane 5 launcher towards the International Space Station (ISS). After several phasing, parking and rendezvous demonstration days, the ATV autonomously completed its docking to ISS with success on 04/03/2008. On 09/05/2008, the ATV undocked ISS, then performed maneuvers to re-phase with the ISS and finally initiated its reentry over the Pacific Ocean on 09/29/2008. This paper deals with the description of the actual maneuver plans computed by the CNES Flight Dynamic Team all along the mission.

AAS 09 – 173

Navigation Analysis of the Trajectory Correction Maneuvers on Approach to the Pluto Encounter for the New Horizons Mission, Using Lorri Only

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Navigation studies of the required statistical maneuvers in the Pluto approach phase of the New Horizons mission have been performed. Analysis of the spacecraft position knowledge and control errors, with varying number and placement of the final maneuvers from 100 to 10 days prior to Pluto closest approach, were simulated. The effect of varying the orbit determination data cutoff prior to the maneuver design, an important operational consideration, was characterized. A Monte Carlo analysis was performed based on orbit determination knowledge errors, based largely on images obtained from the Long Range Reconnaissance Imager (LORRI), and required maneuver execution errors to investigate uncertainties in the control to the Pluto B-plane target, as well as the delta-v expended. A comparison of knowledge and control requirements is made, and an optimal maneuver strategy is determined.

AAS 09 – 174

New Horizons Pluto Approach Navigation: The Effect of Nix And Hydra on Time of Flight Knowledge

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This paper describes the results of an analysis to update the navigation uncertainties in time of flight expected for the New Horizons spacecraft on the approach to Pluto. This updated analysis incorporates the effects of the newly discovered satellites, Nix and Hydra, on the Pluto approach uncertainties and utilizes the latest optical navigation (OpNav) image schedule. The required Pluto approach navigation accuracy for New Horizons depends on the desired accuracy of several key geometric parameters of interest to science. Examples are science instrument pointing angles and accomplishing Pluto and Charon occultations of the Earth during the Pluto flyby. In particular, science would benefit if the time of flight error can be reduced. In this paper, the knowledge of spacecraft position along the trajectory, or time of flight error, for various options of processing OpNav images of Pluto and its satellites is presented. The OpNav scenarios are part of an overall navigation plan that includes the use of DSN radio metric data and current assumptions on *a priori* uncertainties for the Pluto system ephemerides.

AAS 09 – 175

Near-Optimal Steering Analysis for a Slow-Push Mission to Deflect Apophis

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We examine the effectiveness of a near-optimal steering strategy for a gravity tractor mission to deflect asteroid Apophis from the possible passage through a keyhole in 2029. Direct optimization of the tug vector is compared against along track tugging using patched conics analysis. The objective is to maximize Apophis' perigee distance. Results suggest that a steering strategy may more effective than along-track tugging to maximize perigee distance when a deflection mission is implemented with short lead times prior to close encounter. For long lead times tugging along the velocity vector showed to be more effective to maximize flyby distance.

SESSION 12: ADVANCED ATTITUDE SENSORS SPECIAL SESSION
Chair: Dr. Brian Kawauchi, The Aerospace Corporation

AAS 09 – 176

The Hemispherical Resonator Gyro: From Wineglass to the Planets

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Small size, low noise, high performance and no wear-out has made the Hemispherical Resonator Gyroscope (HRG) the choice for high value space missions. After 14 years of production the HRG boasts over 12-million operating gyrohours in space with 100% mission success. But to get to this point has been a struggle. This paper will describe the HRG's elegant simplicity in design and operation and trace its genealogy from concept to the future. Its versatility will be shown by its use for spacecraft stabilization, precision pointing, aircraft navigation, strategic accuracy systems, oil borehole exploration and planetary exploration.

AAS 09 – 177

Precision Navigation Sensors Based on Cold Atoms

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Recent advances in the quantum-level control of atoms using light has resulted in the evolution of a new class of high performance inertial sensors, including accelerometers, gyroscopes and gravity gradiometers. This paper will present basic operating principles and discuss performance of current and envisioned future generation sensors and systems.

AAS 09 – 178

Integrated Ultracold Atom Chip Gyroscopes

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It has long been appreciated that matter wave interferometers have a Sagnac sensitivity to rotation is many orders of magnitude greater than that for light. While rotation sensing needs provided significant motivation to develop atom based sensors, atom interferometry has proven to be a very capable paradigm for high performance inertial sensing applications in general. Considerable progress has been made and much of the significant progress is reviewed in this same conference session. In the last decade, science saw the birth and evolution of ultracold matter with the first demonstration of the Bose-Einstein Condensate, or BEC. Acknowledged as the atom analog of the optical laser, one considers the impact that the BEC and related forms of ultracold matter may have on atom interferometry. The past several years have witnessed the emergence of so-called "atom-chip" technology, which has led to the miniaturization of ultracold atom systems and which is now looking to enable small yet high performance ultracold atom interferometers.

AAS 09 – 179

Attitude Sensors on a Chip: Feasibility Study and Breadboarding Activities

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‡‡ European Space Agency – The Netherlands.

The advent of MEMS and tiny-scale CMOS technology enabled a significant miniaturisation trend on consumer electronics' Electro-Optical devices. ESA technology developments follow this trend, using for the first time MEMS applications in space (e.g. MEMS rate sensors, micro-shutters, micro-thrusters) and highly-integrated CMOS image detectors. Within ESA TRP, the team runs a feasibility study for the application of micro-technologies to on-a-chip sun sensors, star trackers and navigation cameras. The "sun sensor on-a-chip" resulted as the most straightforward to be developed in a short/ medium period. The study outlined key areas of technological challenges and a star tracker configuration, with the expected performance.

AAS 09 – 180

Withdrawn

AAS 09 – 181

The Joint Milli-Arcsecond Pathfinder Survey (JMAPS): Mission Overview and Attitude Sensing Applications

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The Joint Milliarcsecond Pathfinder Survey (JMAPS) is a Department of Navy bright star astrometric all-sky survey scheduled for launch in the 2012 timeframe. Mission objectives include a complete update of star positions for the 2015 epoch to accuracy levels of 1 milliarcsecond (5 nano-radians) for bright stars, demonstration of 10 milliarcsecond attitude determination capability, and 50 milli-arcsecond attitude control on-orbit. In the following paper, we describe the general instrument design and expected performance. We also discuss the new mission capabilities enabled by this unprecedented attitude determination accuracy, and focus specifically on the application to long distance (50,000-100,00 km) formation flying and solar system navigation.

AAS 09 – 182

Qualification of the APS Based Star Tracker to be Flown on the Alphabus Platform

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The APS Star Tracker activities started in Galileo early in 2002, within an ESA contract dedicated to the development of a Demonstration Model (DM) to secure the technology for the future Bepi Colombo ESA mission to the planet Mercury. This contract showed the feasibility of a compact, light and simple star tracker based on APS detector. As a follow on, Galileo was awarded another contract from ESA, devoted to the realization of a Flight Configuration Model (FCM) of the Bepi Colombo sensor, to be flown as an experiment on the PROBA-2 satellite, currently scheduled for a launch within 2008. Today, Galileo has completed the development and on-ground qualification of an APS based star tracker dedicated to the ALPHABUS platform product line for GEO Satellite Telecommunication (TLC) applications. The sensor configuration for ALPHABUS has several characteristics in common with the sensor configuration that Galileo will fly on board PROBA-2. The EQM has been subjected to a full qualification campaign, including electrical, functional, performance and environmental tests. The Flight Models for AlphaBus, Bepi Colombo and other Commercial programs are currently at various stages of their manufacturing process, confirming the market demand for this new product. In this paper an overall description of the AA-STR is reported, together with the main results obtained from its qualification campaign.

AAS 09 – 183

Next Generation Inertial Stellar Compass

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Draper Laboratory's Inertial Stellar Compass (ISC) is an attitude determination system with accuracy better than 0.1 degree at very low power and mass. The ISC has been successfully flight validated on the TACSAT-2 spacecraft and marks for the first time Draper MEMS gyros have been operational in space. Since its initial development by Draper Laboratory in 2001, both MEMS technologies and APS technologies have advanced, making possible an order of magnitude improvement in attitude accuracy while keeping the power and mass metrics nearly the same as the original design. This paper describes the proposed system and development to realize the next generation ISC.

SESSION 13: RENDEZVOUS, RELATIVE MOTION, FORMATION FLIGHT, AND SATELLITE CONSTELLATIONS 2
Chair: Dr. Thomas Starchville, The Aerospace Corporation

AAS 09 – 184

Electrostatic Spacecraft Collision Avoidance Using Piece-Wise Constant Charges

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This paper develops a three-phase piece-wise constant spacecraft charge maneuver to achieve an short-range collision avoidance with a symmetric relative trajectory. This symmetric trajectory guarantees collision avoidance, restores the original relative motion direction, and keeps the relative change in kinetic energy level the same as the initial one. The paper first presents an analytical solution to calculate a unique symmetric trajectory when the middle phase is a circular trajectory. Next a general symmetric trajectory programming strategy is developed where the middle-phase can be any conic section. Four constraints are required to guarantee a symmetric collision avoidance trajectory, while five independent variables are required to solve the problem. This leaves one degree of freedom (DOF) which is utilized to optimize the trajectory subject to specific cost charge functions. There is a duality in the charge solution when solving for the open-loop trajectory with one of the solutions being false. This is addressed by properly initializing and confining the region of the numerical search routine. Minimum charge criteria are determined to avoid a collision by analyzing the geometric properties of the two-body system and comparing the results from circular transitional trajectory calculations.

AAS 09 – 185
Withdrawn

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Formation Flying: Relative Orbits' Modelling and Control Through Eulerian Orbital Elements

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This work deals with the dynamics of spacecrafts in formation. The relative motion is described through the difference between the Eulerian orbital elements of the deputy satellite and the chief's ones. Eulerian orbital elements are defined from the constants of motion of the Intermediary Motion: they include perturbations till part of the 4th zonal harmonic of the Earth's gravity potential. A target relative motion insensitive up to the J_3 is defined by matching the time variations of the Eulerian angular elements. Reconfiguration manoeuvres are performed by a relative orbit control where errors in the orbital elements are fed-back.

AAS 09 – 187

Formation Keeping and Maneuvering for Astronomical, Dual Spacecraft Formation Flying Missions

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Typical astronomical satellite missions maintain inertial pointing over extended periods. In the case of a distributed observatory formed by an optical assembly and a detector assembly flying in formation, the challenge is to keep the formation aligned inertially to within tight tolerances, while counteracting the natural tendency to formation disgregation. We investigate strategies for acquisition, keeping and reconfiguration of the formation to satisfy an observational schedule. Simulations are carried out accounting for all relevant forces and using Lambert targeting and differential corrections for coarse and fine formation acquisition and reconfiguration. Formation keeping is simulated based on a thrust profile derived from a simple theorem of relative motion. Simulations are performed simply as a forward modelling problem without closed loop control of the chaser. Thruster and orbital restitution uncertainties are modelled. A set of X-ray sources has been adopted from the XMM mission as observation targets for implementation of the observational schedule subject to several viewing constraints. The resulting thrust and fuel consumption profiles are provided corresponding to different operational strategies, together with their evaluation of their effectiveness.

AAS 09 – 188

Perturbation Model for the High Elliptical Formation Orbits (HEO)

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The paper presents an analytical model of the relative motion of satellites in a formation on HEO that include the influence of geopotential coefficients up to arbitrary degree and order, luni-solar effects and solar radiation pressure. Formulas for differential perturbations have been transformed to the form enabling their application to the high elliptical orbits. Values of the eccentricity function are obtained with use of a special procedure that enables stable calculations for all values of the eccentricity less than 1. The presented model can by use for precise predictions of the relative motion of satellites in a formation. Perturbation models were analyzed for different types of formation flying architectures, including in-plane and out-of-plane formations, and for different types of spacecrafts (with different area to mass S/m ratio). In particular, the paper presents results for the SIMBOL-X, PROBA-3 and MMS missions.

AAS 09 – 189

Rotating Symmetries in Space: The Flower Constellations

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Flower Constellations is a novel methodology to design axial-symmetric satellite constellations whose satellites all belong to the same closed trajectory in a prescribed rotating reference frame. These constellations highlight the existence of new, unexpected, shape-preserving rigid-body objects rotating with specific angular velocities. In this paper, the fundamentals of Flower Constellations theory is revisited in a very general way and new important parameters, such as the "*Flower Mean Anomaly*" and the "*Configuration Number,*" are derived to classify and describe the Flower Constellations.

AAS 09 – 190

The Two-Dimensional Equatons of Perturbed Relative Motion

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The very restricted four-body problem is used to derive linearized equations of relative motion that take into account the perturbing effects of a secondary gravitational source. The result is a system of linear differential equations that has an analytical solution. The results of this solution are compared to the outcomes of the very restricted four-body problem and the well known Hill-Clohessy-Wiltshire equations for various cases in the Sun-Ceres system. The results demonstrate that the Benavides-Spencer formulation's accuracy exceeds that of the Hill-Clohessy-Wiltshire equations when compared to the real-life outcomes returned by the numerical integration of the very restricted four-body problem.

AAS 09 – 191

The Use of Satellite Constellations and Formations for Future Satellite Gravity Missions

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The monitoring of Earth's gravity field from space has witnessed great progress through the launch of several dedicated satellite missions over the past decade, but the mission lifetimes for all of these missions are projected to end within the next five years. Looking forward to potential follow-on missions, there are limitations in the current gravity field missions that might be overcome through the use of modified formation designs, or even through the use of satellite constellations. Through a series of simulated mission scenarios, this study will show that by combining a dedicated gravity field mission together with a constellation of (non-dedicated) satellites, the recovery of the gravity field across the full spectrum of signals (both spatial and temporal) can be dramatically improved. Furthermore, the proposed mission concept is based primarily on existing technology, and could conceivably be realized in a fairly short time frame (i.e., less than five years).

SESSION 14: TRAJECTORY DESIGN AND OPTIMIZATION 1
Chair: Dr. William Cerven, The Aerospace Corporation

AAS 09 – 192

Automated Lunar Free Return Trajectory Generation

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A lunar free return trajectory generation algorithm is developed with patched conic and circular restricted three body models. With limited user input, the algorithm constructs an initial guess of both the trans-lunar injection velocity and time of flight. Once the initial trajectory is found, a system of nonlinear equations is solved numerically to target earth arrival conditions leading to a feasible free return trajectory. Possible free returns include departures from both prograde and retrograde earth orbits coupled with circumlunar or cislunar flight, in and out of the earth-moon plane. The advantage of this method over previous methods is that no trial and error is required to generate the initial guess.

AAS 09 – 193

Repeat Ground Track Methods for Earth Observation Satellites: For Use in Optimization Algorithms

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This paper investigates three methods for numerically determining the condition for repeat ground tracks. The basic analytical condition for a repeat ground track is established followed by a short review of two recent methods. Then a third method is introduced. The advantages and disadvantages of each approach are weighed with each method's reliability, performance, and computational ease based on a case study. From these criteria, one method is recommended for use in an optimization algorithm.

AAS 09 – 194
Withdrawn

AAS 09 – 195

Initial Trajectory Model for a Multi-Maneuver Moon to Earth Abort Sequence

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To support the mission design and trajectory design problems associated with the Moon to Earth trajectories for the Crew Exploration Vehicle (CEV), we develop the starting trajectory model that serves as the first iterate for a complete targeting and optimization procedure that takes a spacecraft from any closed lunar parking orbit ($0 \leq e < 1$) to the Earth entry interface state for any date. The motivation for this work is to examine the "any time abort" capability required for the CEV human Moon mission. The maneuvers are either impulsive or fixed direction finite burns, though the results presented here are limited to impulses. An analytical procedure is developed that constructs a multi-impulse escape trajectory from the Moon propagated forward in time and a backward propagated trajectory from the Earth with a mismatch in position and velocity near the sphere of influence of the Moon. The position and velocity discontinuities at the mismatch point are small enough to lie within the convergence envelope of simple gradient based differential correction procedure that can, at a minimum, generate a feasible solution. The efficiency of the method is illustrated by solving any-time-abort transfer problems typical for a human mission.

AAS 09 – 196

Withdrawn

AAS 09 – 197

Withdrawn

AAS 09 – 198

Optimal Collision-Free Trajectory Planning for Robotic Manipulators: Simulation and Experiments

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Trajectory planning for robotic manipulators is a challenging problem that continues to receive a great deal of attention. This paper demonstrates the applicability of pseudospectral optimal control to solve the motion planning problem for a two-link robotic arm. Minimum-time point-to-point maneuvers in the absence and presence of workspace obstacles are considered. Incorporating kinodynamic constraints on the manipulator joint angles, velocities and accelerations, as well as control torque limits into the optimal control formulation ensures the computed solutions are physically realizable. The feasibility of the numerical results is verified by executing the computed trajectories on an experimental robotic manipulator.

AAS 09 – 199

Averaging and Mission Design: The Paradigm of an Enceladus Orbiter

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Preliminary mission design for planetary satellite orbiters requires a deep knowledge of the long-term dynamics that is typically obtained through averaging. In some cases the validity of the averaging is limited to prohibitively small regions, thus, depriving the analysis of significance. We find this paradigm at Enceladus, where the validity of a first order averaging based on the Hill problem lies inside the body. This inconvenience does not invalidate the technique, and perturbation methods are used to reach higher orders in the averaging. Proceeding this way, we average the Hill problem up to the sixth order obtaining valuable information on the dynamics close to Enceladus.

AAS 09 – 225

Flying By Titan

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The Cassini spacecraft encounters the massive Titan about once every month. These encounters are essential to the mission as Titan is the only satellite of Saturn that can provide enough gravity assist to shape the orbit tour, which will allow outstanding science for many years. From a navigation point of view, these encounters provide many challenges. In particular, those that fly close enough to the surface for the atmospheric drag to perturb the orbit. This paper discusses the dynamic models developed to successfully navigate Cassini and determine its trajectory. This includes the moon's gravity pull with its second degree zonal harmonics, J_2, the attitude control perturbations and the acceleration of drag.

SESSION 15: ATTITUDE SENSING, ESTIMATION, AND CALIBRATION 2
Chair: Dr. Don Mackison, University of Colorado

AAS 09 – 200
Application of the Backward Smoothing Extended Kalman Filter to Attitude Estimation using Radar Observations

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The Lincoln Attitude Estimation System is a new tool being developed for the Space Situational Awareness Group at Lincoln Laboratory. The system employs a modified backward-smoothing extended Kalman filter (BSEKF) to produce an attitude determination process that can be integrated with a collection of legacy hardware and software systems currently in use at Lincoln Laboratory. The new filter uses a non-traditional measurement process which involves the fit of geometric satellite models to discrete-time radar images. The major alterations that have been made to the BSEKF include the addition of environmental torque models and a geometrically-derived inertia matrix that removes the assumption of symmetry in the principal moments of inertia and includes estimates for the off-diagonal products of inertia. The algorithm has been tested using simulated and actual data from a challenging spacecraft attitude estimation problem with significant dynamic model uncertainty. The filter compensates for this uncertainty by means of concurrent estimation of moment of inertia parameters and has been demonstrated to have accurately and reliably converged on a motion solution in both test cases.

AAS 09 – 201

Estimation and Calibration of Alignment Change Between Precision Star Sensors

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Improvements in accuracy of star sensors revealed that alignment changes between star sensors became a dominant factor preventing precise attitude determination. The Advanced Land Observing Satellite (ALOS) launched on January 24, 2006, introduced a newly developed precision star tracker having three optical heads. On-orbit calibration of sensor alignments for this star tracker, however, revealed an anomaly affecting attitude determination accuracy. Orbit periodic changes and long-term temporal changes were observed in relative alignments between its optical heads and are mainly caused by thermal distortion of an attachment bracket of the satellite structure. These alignment changes were modeled and an approach to estimate them was developed. Periodical estimation of the alignment changes was performed and derived alignments were updated to compensate those changes in ground-based attitude determination to maintain its accuracy.

AAS 09 – 202

Extended Kalman Filter for MMS State Estimation

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The Magnetospheric MultiScale Mission is a four spacecraft formation flying mission designed to study the Earth's magnetosphere. The spacecraft fly in highly elliptical orbits, forming a tetrahedron at apogee. Each spacecraft spins at 3 RPM and is equipped with a star scanner, slit sun sensor, and accelerometer. The purpose of this work is to develop an Extended Kalman Filter to simultaneously estimate the attitude, angular velocity, angular acceleration, and center of mass of each spacecraft.

AAS 09 – 203

Gyro Misalignment Decomposition Applied to MESSENGER Calibration

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In attitude sensor misalignment estimation, a rotational misalignment vector, or a linear combination of rotational misalignments, must be constrained to zero for full observability. For this reason, one attitude sensor is generally designated the body reference sensor. Alternatively, the Inertial Measurement Unit (IMU) can be the body reference sensor. A method for removal of a rotational misalignment from a Redundant IMU (RIMU), which has more than three sense axes, was developed recently. We demonstrate the method using telemetry from the MESSENGER spacecraft. Results are compared with earlier results where one star tracker is the body reference sensor.

AAS 09 – 204

Further Study on Attitude Acquisition of a Satellite With a Partially-Filled Liquid Tank

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The wheel spin-up for spacecraft reorientation using a momentum transfer technique is limited by the amount of available satellite power, and by the allowed time period for the maneuver. Therefore, determination of the desired spin-up strategy and acquisition time constant are primary issues in a momentum transfer maneuver. In this study, an analytical method to determine an appropriate wheel spin-up scheme and the acquisition time constant is developed and compared to numerical simulations and show excellent agreements.

AAS 09 – 205

Kalman Filter Based Multimode Attitude Determination Algorithms for a LEO Satellite

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This study presents the design of a Kalman filter based attitude determination algorithms for a hypothetical LEO satellite with a multimode structure that employs different sensor combinations and as well as online switching between these combinations depending on the sensor availability. The performance and effectiveness of these different attitude determination modes and the multimode structure are investigated through simulations. Especially the accuracy of the state estimation and the behavior of the system covariance matrix on the mode transition phases are presented. In conclusion, performance comparison for a successive attitude maneuvers and for a fixed attitude hold maneuver between the asynchronous multimode structure and accurate mode having synchronous sensor measurements are discussed.

AAS 09 – 206

Attitude Determination from Light Curves via Unscented Kalman Filtering

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A quaternion-based unscented Kalman filter (UKF) was used to recover attitude parameters and body rates for a simulated object of known shape and surface characteristics by reducing the light curve (observed brightness as a function of time) of a specific object. Synthetic data were generated for a sunlit cylinder in a geosynchronous transfer orbit, as observed from a specific ground site and corrupted by a white noise process. The light curve data were then reduced by the UKF (using the same observation model as the one which generated the synthetic measurements) to recover the attitude and rotation rate of the cylinder. The results were then compared to the known truth data as a means of quantifying filter performance.

SESSION 16: FLIGHT DYNAMICS OPERATIONS AND SPACECRAFT AUTONOMY
Chair: Dr. Michael Gabor Northrop Grumman

AAS 09 – 207

Overview of ATV Flight Dynamics Operations from Separation to Docking

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On 09 March 2008, the first Automated Transfer Vehicle of the Jules Verne mission lifted off from Kourou aboard the Ariane 5 launcher towards the International Space Station. It was the first European automated spacecraft which has ever docked autonomously to the ISS. This paper presents the overview of the ATV Jules Verne Flight Dynamics operations from LEOP to Docking, including the unforeseen events that the Flight Dynamics System met and how it managed them.

AAS 09 – 208

Automated Transfer Vehicle (ATV) "Jules Verne" Flight: Real-Time GNC Monitoring at ATV-CC/FDS – Concepts and Mission Results

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ATV Jules Verne, as the first of a series of highly automated space vehicles, gave the possibility to implement some new approaches to increase mission reliability confidence: the real-time monitoring of GNC functions. This has been implemented through consistency checks with respect to ground tools of same nature or with respect to predicted absolute/relative trajectory and attitude profiles or boost commands. All along the Jules Verne mission, real-time GNC monitoring has successfully operated. This paper highlights the concepts of the ATV GNC monitoring, details its implementation and discusses the results obtained during the Jules Verne mission.

AAS 09 – 209

Management of Unforeseen Events by Flight Dynamics Team During ATV Jules Verne Operations

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On 09 March 2008, the first Automated Transfer Vehicle of the Jules Verne mission lifted off from Kourou aboard the Ariane 5 launcher towards the International Space Station. It was the first European automated spacecraft which has ever docked autonomously to the ISS. This paper describes the unforeseen events that FDS (Flight Dynamics System) met during Jules Verne operations and how it managed them.

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Withdrawn

AAS 09 – 211

Heuristic Approach for Satellite Mission Scheduling

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Heuristic approaches for satellite mission scheduling using the genetic algorithm are presented in this paper. As satellite control and operation techniques have been developed, satellite missions to perform became more complicated and overall quantity of missions also increased. These changes require more specific consideration and a huge amount of computation for the satellite mission scheduling. Therefore, it is essential to research and develop an optimization algorithm that makes an optimal satellite mission schedule by considering mission parameters and constraints simultaneously. For this reason, many scheduling programs use heuristic algorithms such as tabu-search, genetic algorithm, neural network, etc. as scheduling algorithms. In this paper, the genetic algorithm is researched and analyzed as a satellite mission scheduling algorithm. The research on the combinations of processing methods is performed. Simulations on the actual satellite mission scheduling problem are also considered and accomplished based on the previous simulation result.

AAS 09 – 212

Cooperative Control for Satellite Formation Reconfiguration Via Cyclic Pursuit Strategy

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This paper investigates a methodology for group coordination and cooperative control of satellites with the aim to achieve formation reconfiguration such as radius enlargement and phase angle adjustment. The proposed approach separates the control law into two distinct stages: planar movement control and orthogonal displacement suppression. The in plane approach is based on a cyclic pursuit strategy, where satellite i pursues satellite $i+1$. For phase angle adjustment, a control law that makes use of 'beacon guidance'is synthesized to maintain the circling centre stationary. In the orthogonal direction, a linear feedback control on displacement and velocity is used. The local stability of the whole system is also analyzed. Simulation of two missions with different propulsion systems are provided, which highlight the thrust setting strategy and the overall effectiveness of the proposed approach.

SESSION 17: OPTIMIZATION
Chair: Dr. Chris Ranieri, The Aerospace Corporation

AAS 09 – 213

An Adaptive and Learning Approach to Sampling Optimization

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This paper provides a methodology to rapidly and accurately explore the cost function of an optimization problem based on rejection sampling. Initial results show good precision and rapid convergence. This leads to numerous applications where a multi-minima problem must be optimized or solved, such as those seen in control problems, optimal orbit maneuvers, or constellation design. The approach will be shown to be adaptive and to cover mixed integer-real functions.

AAS 09 – 214

Optimal Thrust Design of a Mission to Apophis Based on a Homotopy Method

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A novel homotopy method for solving optimal thrust direction control problems through Pontryagin's principle is presented. The homotopy method enforces the satisfaction of the dynamic equation constraints along the homotopy path, yielding an algorithm that is robust to the high nonlinearity of both dynamic equation constraints and performance criteria. The homotopy approach extends the convergence domain of the initial guess of the unknown boundary conditions when compared to the sequential quadratic programming method. The homotopy algorithm is applied to an Earth to Apophis mission analysis. A hybrid impulsive and low thrust propulsion strategy is studied. Through simulation results, we prove that if we use a 0.05*N* constant thrust and choose the time of flight from 250 days to 300 days, the launch window for the Earth to Apophis mission can span a full year from April 2012 to April 2013 for a standard launch vehicle.

AAS 09 – 215

Applications of an Evolutionary Strategy on General Perturbation Equations for Optimization of Low-Thrust Near-Earth Orbit Transfers

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With recent developments in low-thrust optimization techniques, several methods of trajectory optimization can be implemented across various transfers. Much recent work has focused on performing methods of optimal control on low-thrust, near-Earth orbit transfers, achieving maximum efficiency in both energy use and time-of-flight. However, the use of optimal control relies on the exploitation of a satellites' equation of state, which becomes problematic if optimization is to be performed through a venue where the state equations cannot be manipulated. This situation is particularly evident when attempting to perform trajectory optimization through a commercial off-the-shelf satellite mission modeling software package. Thus, a robust optimization method must be chosen to produce competitive results comparable to optimal control in these types of situations. However, the formulation of an objective function, as well as which type of optimization method to choose is important, since some formulations or algorithms may lead to better or faster convergence when compared to others. Previous work has been devoted to assessing which optimization algorithms work best within a "black box" commercial software package, in which an evolutionary strategy was found to be the most robust. In this study, a near-Earth low-thrust trajectory will be modeled in Satellite Toolkit's Astrogator® with an evolutionary strategy applied. An appropriate objective function, and problem formulation in STK based on general perturbation equations is optimized within this evolutionary strategy, in an attempt to create a optimization method which can produce results on par with those found using a method of optimal control.

AAS 09 – 216

Iterative Learning Control in Nonlinear Systems Using State Estimation for Relinearizations

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Iterative learning control (ILC) applies to systems performing a tracking maneuver repeatedly. The error in each run is used to adjust the command in the next run, aiming to converge to zero error. Spacecraft applications include making fine pointing equipment follow a precise scan pattern in spite of flexibility effects. Previous papers showed how to use effective linear ILC laws in the neighborhood of a desired trajectory of a nonlinear system, and also, how to impose inequality constraints on actuator signals during the learning process in linear systems. This paper shows how to extend the range of convergence, by performing repeated relinearizations which requires simultaneous estimation of the state history. Attention is addressed to the need to know the state history, not just the output history for the trajectory about which one wants to linearize. In addition, attention is focused on the fact that ILC aims for zero tracking error in hardware, and the input needed for this will be somewhat different than the one that gets zero error in the mathematical model that is used in designing the ILC law.

AAS 09 – 217

Modeling Perturbations and Operational Considerations When Using Indirect Optimization With Equinotical Elements

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Using equinoctial elements with indirect optimization methods, a generalized formulation is developed to incorporate various orbital perturbations resolved in the inertial system. This formulation allows the effects of the perturbations to be easily included in the equinoctial force model and the corresponding co-state equations for minimum-time trajectories. Analytic expressions for all the necessary derivatives are presented in a concise framework. This framework allows a more detailed force model to be used with equinoctial elements in an indirect optimization scheme than have been used to date. Additionally, operational concerns are addressed to allow mission-specific coast arcs to be placed optimally. Results are presented showing the effects of various perturbations (third bodies, zonal harmonics, and solar radiation pressure) and the placement of coast arcs on an example GTO to GEO transfer.

AAS 09 – 218

Optimal Continuous-Thrust Trajectories Via Visual Trade Space Exploration

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Engineering design problems often contain correlations and tradeoffs that may or may not be obvious or well-understood. As design problem complexity increases, decision makers find it more and more difficult to grasp these tradeoffs effectively. The rapid growth of computing power now allows the simulation of millions of design alternatives, and the ability to effectively visualize these alternatives and understand the tradeoffs associated with them has never been more important. Trade space visualization tools are designed to aid decision makers by allowing them to effectively explore a design space and grasp the underlying tradeoffs and nuances particular to their specific problem. These tools provide great potential in evaluating complex dynamical systems in the aerospace industry, among others. In this paper, we apply our trade space visualization software, the Applied Research Lab Trade Space Visualizer (ATSV), to search for optimal constant thrust and constant acceleration orbit transfers. This problem is formulated as a multiobjective optimization problem where it is desirable to explore various competing objectives. First, we identify a known optimal solution and explore the input space to search for other optimal or near-optimal trajectories. The problem is then modified to include the discrete hardware-side design variable, engine type, and optimal solutions are found for each corresponding design variable option. Finally, a study is performed to understand the sensitivity of found optimal trajectories to perturbations of the initial orbit.

AAS 09 – 219

Improvements in Pseudospectral Based Hypersonic Vehicle Trajectory Generation Via Enhanced Aerothermal Prediction Methods

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Hypersonic vehicle re-entry trajectories are traditionally formulated as a constrained two point boundary value problem which consider a variety of problem related path constraints. The solutions to these two point boundary value problems are found by employing numerical optimization techniques such as the accelerated projected gradient method or pseudospectral optimization techniques. Initial, terminal, and path constraints are used to describe the problem to be analyzed and are generally problem specific. For extended endoatmospheric hypersonic flight, the total aerothermal heat and heat flux imparted on the flight vehicle becomes a critical path constraint to consider when generating an optimal trajectory solution. Heat calculations used in these cases, however, tend to be simplified to closed form representation that solely consider stagnation heating to limit the constraint complexity. The Gauss pseudospectral optimization method has been shown to provide excellent solution convergence for highly constrained trajectory problems. This paper evaluates the performance of the Gauss pseudospectral optimization method in generating long flight duration hypersonic vehicle trajectories considering complex aeroheating calculations as path constraints.

SESSION 18: MISSION DESIGN 2
Chair: Yanping Guo, APL

AAS 09 – 220

Orbit Mechanics About Small Satellites

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Space missions to small solar system bodies must deal with multiple perturbations acting on the spacecraft. These include strong perturbations from the gravity field and solar tide, but for small bodies the most important perturbations may arise from solar radiation pressure (SRP) acting on the spacecraft. Previous research has generally investigated the effect of the gravity field, solar tide, and SRP acting on a spacecraft trajectory about an asteroid in isolation and has not considered their joint effect. In this paper a more general theoretical discussion of the joint effects of these forces will be given. Also derived is a general solution for the averaged motion of a spacecraft about a point mass in orbit about the sun due to perturbations from solar radiation pressure.

AAS 09 – 221

Applications of Chaoticity Indicators to Stability Analysis Around Small Bodies

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The characterization of regions of long-term stable motion of a small body orbiter is addressed using fast Lyapunov indicators in combination with periodic orbit families computations. In particular the feasibility of computing dynamical maps for such systems is demonstrated and the calibration of the method in relation to the particularities of asteroid dynamics, such as the irregular gravitational field and importance of the solar radiation pressure, is discussed. Sequences of maps around the asteroid 6489 Golevka reveal the role of the various perturbations and the existence of very-long term stability regions near terminator orbits, where a spacecraft without any control would orbit the small body for several decades. The regions are shown to be limited in size and influenced by low order mean motion resonances. The method represents a complementary approach to the analytical results available in the literature when averaging assumptions do not apply or quantitative, accurate information is needed for a particular small body, and should thus be helpful for mission designer in determining the available trajectory options for specific missions.

AAS 09 – 222

Pathfinding and V-Infininty Leveraging for Planetary Moon Tour Missions

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The well established technique of V-infinity leveraging is applied to the phase-fixed planetary moon tour problem, and a global analysis of the related design space is performed using an automated pathfinding technique. Resonance hopping transfers between two circular, coplanar moons of a common planet are designed using series of alternating V-infinity leveraging maneuvers and zero-point patched conic gravity assists. When this technique is combined with an efficient global search based on Bellman's Principle, the end result is an exhaustive set of fuel and time optimal trajectories between the two moons in question. The associated Pareto front of solutions represents the classic fuel versus flight time trade study sought in preliminary mission design. Example numerical results are produced for orbital transfers between scientifically interesting moons in the Jovian system. Finally, resonant transfers of neighboring pairs of moons are patched together to obtain fuel and flight time estimates for a full Jovian system tour with intermediate science orbits. Results from this fast, preliminary design procedure are intended to serve as useful starting points for higher fidelity multi-body mission design. In general, the resonant hopping design approach and the associated design procedure are found to be most relevant for missions with short flight time requirements.

AAS 09 – 223

Flight Path Control Design for the Cassini Equinox Mission

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The Cassini-Huygens spacecraft has successfully completed its four-year Prime Mission and began a two-year extended mission on July 1, 2008. Officially named the "Equinox Mission", the extended mission includes 95 orbit trim maneuvers designed to achieve flybys of Titan, Enceladus, Rhea, and Dione. This paper gives an overview of maneuver statistical predictions and analysis for the Equinox Mission.

AAS 09 – 224

The Endgame Problem Part A: V-Infinity Leveraging Technique and the Leveraging Graph

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ESA and NASA renewed interest on missions to Europa, Ganymede, Enceladus and Titan poses the question on how to best solve the Endgame problem. Endgames typically aim at a cheap insertion maneuver into the science orbit, and can be designed using either V-Infinity Leveraging Maneuvers (VILMs) or the Multi-Body dynamics. Although historically linked to insertion maneuvers, the endgame problem is symmetric and equally applies to departure. In this paper series, we analyze and draw connections between the two apparently separate approaches, providing insight to the dynamics of multi-body gravity assist problem. In this paper we derive new formulae for the VILM and build the Leveraging Graph to be used as a reference guide for designing Endgame tours. We prove that the cost of a VILM sequence decreases when using high altitude flybys (as done in the Multi-Body technique). Finally, we find a simple quadrature formula to compute the minimum ΔV transfer between moons using VILMs, which is the main result of the paper. The Leveraging Graphs and associated formulae are derived in canonical units and therefore apply to any celestial system with a smaller body in a circular orbit around a primary. Specifically we demonstrate the new method to provide rapid calculations of the theoretical floor values for ΔV requirements for resonant hopping moon tours in the Saturn and Jupiter systems using the VILM model.

AAS 09 – 226

Invariant Manifolds, Discrete Mechanics, and Trajectory Design for a Mission to Titan

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With an environment comparable to that of primordial Earth, a surface strewn with liquid hydrocarbon lakes, and an atmosphere denser than that of any other moon in the solar system, Saturn's largest moon Titan is a treasure trove of potential scientific discovery and is the target of a proposed NASA mission scheduled for launch in roughly one decade. A chief consideration associated with the design of any such mission is the constraint imposed by fuel limitations that accompany the spacecraft's journey between celestial bodies. In this study, we explore the use of patched three-body models in conjunction with a discrete mechanical optimization algorithm for the design of a fuel-efficient Saturnian moon tour focusing on Titan. In contrast to the use of traditional models for trajectory design such as the patched conic approximation, we exploit subtleties of the three-body problem, a classic problem from celestial mechanics that asks for the motion of three masses in space under mutual gravitational interaction, in order to slash fuel costs. In the process, we demonstrate the aptitude of the DMOC (Discrete Mechanics and Optimal Control) optimization algorithm in handling celestial mechanical trajectory optimization problems.

AAS 09 – 227

The Endgame Problem Part B: The Multi-Body Technique and the T-P Graph

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ESA and NASA renewed interest on missions to Europa, Ganymede and Titan poses the question on how to best solve the Endgame problem. Endgames typically aim at a cheap insertion maneuver into the science orbit, and can be designed using either V-Infinity Leveraging Maneuvers (VILMs) or the Multi-Body dynamics. Although historically linked to insertion maneuvers, the endgame problem is symmetric and equally applies to departure. In this paper series, we analyze and draw connections between the two apparently separate approaches, providing insight to the dynamics of multi-body gravity assist problem. In this paper we study the anatomy of the Multi-Body approach using a new graphical tool, the Tisserand-Poincaré (T-P) graph. The T-P graph shows that ballistic endgames are energetically possible and it explains why they require resonant orbits patched with high altitude flybys, whereas in the VILM approach flybys alone are not effective without impulsive maneuvers in between them. We then explain how to use the T-P graph and the associated concepts to design quasi-ballistic transfers composed by endgames and begingames (the symmetric problems). Unlike previous methods, the T-P graph provides a valuable, energy based, target point for the design of the two parts of the trajectory, and a simple way to patch them. Further, the patch point calculation is straight forward and does not require the often tedious generation of manifolds and their associated intersections. We finally present two transfers. The first transfer is between low-altitude orbits at Europa and Ganymede using almost half the Δv of the Hohmann transfer; the second transfer is a 300-day quasi-ballistic transfer between halo orbits of the Jupiter-Ganymede and Jupiter-Europa. With some 50 m/s the transfer can be reduced by two months. While the results have the most relevant implications at low energy (endgame) levels, the Tisserand integral shows that ballistic multi-body transfers are feasible (given infinite time) for all energy levels across any distance gap.

AAS 09 – 228

Withdrawn

SESSION 19: ORBIT DETERMINATION 2
Chair: Dr. Paul Schumacher, Air Force Research Laboratory

AAS 09 – 229

ATV's Jules Verne On-Ground Orbit Determination

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The Automated Transfer Vehicle (ATV) spacecraft is designed and developed by EADS-Astrium Space Transportation as prime contractor for the European Space Agency (ESA). Centre National d'Etudes Spatiales (CNES) in Toulouse, France has developed the ATV Control Centre (ATV-CC) under ESA contract and is responsible for the spacecraft operations. One of the ATV-CC responsibilities is to perform on-ground orbit determination using GPS measurements with Kalman Filter for monitoring purposes and Least Mean Square methods to obtain accurate position and velocity. This paper discusses our operational software and process employed to perform absolute navigation, to initialize relative on-board GPS navigation (RGPS) with ATV relative state vector, and to monitor ATV-ISS relative navigation before docking. Operational results, post flight analysis, comparison results with on-board navigation system, and compliance results with demonstration criteria and joint ATV-ISS flight rules are presented.

AAS 09 – 230

Development of the Technique for Covariance Prediction Using the Gravity Color Noise

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The conventional approach to estimation and prediction of orbits uncertainty is based on using the equations of motion, in which the random disturbances are either not taken into account, or assumed to be represented by white noise. The following questions are considered in the paper:

1. Basis of the technique for covariance prediction. The analysis of the differential equations for forecasting a correlation matrix of state vector errors and their solution are executed. It is necessary to take into account mutual correlation of state vector errors with colored noise for maintenance of a correctness of results. The technique for estimation of matrix function of mutual correlation during orbit determination is considered.

2. Statistical characteristics of the gravity disturbing forces. The problem on a choice of harmonics degree which is taken into account in the motion model is considered. The dependence of the recommended degree on altitude and accuracy of constants C_{nm} and S_{nm} is constructed. The estimation of correlation functions of gravity disturbing forces in the Body-fixed, and also in the Earth-centered inertial coordinate systems is presented. The correlation functions for the resonance satellites in the LEO and GEO, and also for the objects of GPS type are considered in detail.

AAS 09 – 231

Circular and Zero-Inclination Solutions for Optical Observations of Earth-Orbiting Objects

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Situational awareness of Earth-orbiting particles is important for human extraterrestrial activities. Given an optical observation, an admissible region can be defined over the topocentric range and range-rate, with each point representing a possible orbit for the object. However, based on our understanding of Earth orbiting objects, we expect that certain orbits in that distribution, such as circular or zero-inclination orbits, would be more likely than others. In this research, we present an analytical approach for describing the existence of such special orbits for a given observation pass, and investigate methods of finding them by means of singularities in orbital elements.

AAS 09 – 232

Orbit Determination and Propagation of Objects with High AMR for Orbital Archive Maintenance

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Recent research has revealed that objects with high AMR (usually more than 1 sq.m/kg) represent a significant portion of the GEO population and are usual among objects on GTO and other elliptical orbits. Their orbit is highly perturbed by solar radiation pressure, and this perturbation far exceeds all other perturbations. The paper presents methods and algorithms for the orbit determination and propagation for high AMR objects. An algorithm for the joint determination of the orbital parameters and the acceleration vector from the solar radiation pressure with a-priori information is developed.

AAS 09 – 233

Satellite Conjunction Monte Carlo Analysis

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This work uses a simplified Monte Carlo process to assess the satellite collision probability computations of various methods and to obtain a preliminary estimate on their bounds of utility. The process starts with a simple two-body analytical propagation of the position and velocity vectors and their associated 6x6 covariance from epoch to the time of closest approach (TCA). Each object is assumed spherical and a time span is set about the initial TCA to bound the results. No assumptions are made regarding the constancy or direction of the relative velocity over the encounter's time span. The epoch vectors are randomly perturbed in accordance with the initial covariance matrix values and a collision determination made if the relative distance at any time in the span is equal to or less than the combined object radius. Two statistical bounding criteria are used to determine the minimum number of cases needed. The Monte Carlo results are then compared to probability computations that use the unperturbed orbital data at TCA. This particular work does not attempt to simulate real-world perturbations such as atmospheric drag and/or various gravity fields, but rather assures the consistency of the Gaussian process from epoch to closest approach point for the chosen force model. Because no unique or complicated force models are used the results can be easily repeated and independently validated.

AAS 09 – 234

Satellite Maneuver Detection: A Statistical Certainty Metric

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Statistical certainty metrics are a useful tool in satellite maneuver detection. They can provide insight into the size of a maneuver and the likelihood of a detected maneuver being real. This paper provides discussions of which detection criteria are useful for geosynchronous satellites. Results of using two different methods to construct a metric are shown. These methods include one using probability density functions and one using the maneuver detection data from each criterion. Results for the certainty metric are shown for 17 satellites over a span of 500 days with 1349 known maneuvers and 110 known false alarms. As the maneuver size (ΔV) increases over the interval from 0 to 0.4 m/s, the certainty metric yields a 58% increase in probability per 1 (m/s) ΔV. The certainty metric also displays an 8-10% higher probability for real detected maneuvers than detections where no maneuver has taken place.

AAS 09 – 235

Withdrawn

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Satellite Orbit Determination Using Continuous Low-Thrust Modeling

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This study used Optimal Control Theory to model the perturbations caused by continuous thrust. Fuel-optimal trajectories were calculated using numerical optimization techniques. Software was developed to calculate the optimal trajectories and associated thrust plans. A new force model was implemented in GTDS to accept externally generated thrust plans and apply them to a given osculating, i.e. Cowell, or mean, i.e. DSST, satellite trajectory. Test cases verified the correctness of the mathematics and software and also demonstrated that optimal thrust modeling could provide order of magnitude reductions in orbit determination errors for a satellite with low-thrust electric propulsion.

AAS 09 – 237
Tracking Objects With Unknown Dynamics

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This paper discusses techniques that can be used by an imaging system to track an object that has unknown dynamics. A method to estimate an object's velocity from a single image using centroiding is presented. Inertial derivatives present one possible means of estimating motion by assuming linear dynamics. Accuracy of the estimate can be further improved by implementing a continuous-discrete Kalman filter on the measurements. A second method is then presented using non-rational Bézier curves to estimate the dynamics of the object in the image plane. Bézier curves are shown to be a superior method of tracking an object for short periods of time and a viable means of tracking an object exhibiting random walk behavior.

SESSION 20: TETHERS
Chair: Dr. Thomas Lovell, AFRL

AAS 09 – 238
Deployment Control of Electrodynamic Tethers

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The deployment of electrodynamic tethers is important in future applications of conductive tethers in space. Existing work on tethered satellites has focused primarily on the deployment of non-conductive tethers, or the control of electrodynamic tethers after they have been deployed. This paper introduces a strategy for deploying an electrically conductive tether. Instead of constraining the final libration dynamics to be zero at the end of deployment, the controller is designed to deploy the tether into a periodic solution for the in- and out-of-plane librations. Control over the current and rate of change of reel-rate is used to manipulate the deployment dynamics to intersect the terminal manifold created by the librational periodic solution. A feedback controller is also designed for stabilizing the tether librations around the periodic solution by manipulation of the tether length while maintaining the electric current at the nominal value.

AAS 09 – 239

CE2: A CubeSat Electron Collector Experiment

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The Naval Research Laboratory developed an experiment to measure the effectiveness of an electron collection device in space. Electron collection from the plasma surrounding the earth is a key element of an emerging concept for spacecraft propulsion that makes use of the physics principles of electrodynamics. Electrodynamic propulsion offers the prospects of enabling spacecraft to maneuver without the expenditure of conventional fuel, that is the possibility of propellant-less maneuvers. This experiment will measure the effectiveness of narrow metal tapes for collecting electrons from the earth's plasma.

AAS 09 – 240

Exploration of the Jupiter Plasma Torus With a Self-Powered Electrodynamic Tether

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The dynamics and power generation of an electrodynamic tether (EDT) placed in the three body system formed by Jupiter, Io and the spacecraft are analyzed. In the region surrounding Io's orbital path, a region of increased electron density called the plasma torus offers a suitable location to operate an EDT. The electrodynamic interaction between the conducting cable of the EDT and the strong magnetic field of the planet leads to non-negligible electrodynamic force, that perturbs the natural three body motion. New equilibrium positions are found in the synodic frame, which coincide with the classical triangular Lagrangian points only when the electrodynamic force vanishes. The locations of equilibrium positions are computed as a function of tether length, width and spacecraft mass. While in this equilibrium position, the tethered system can generate kilowatts of electrical power without deorbiting the system, the energy coming from to the super-rotating plasma sphere of Jupiter. The motion around the new equilibrium positions is evaluated, for both small linear motion confined to a neighborhood of the equilibrium point, and for large amplitude non-linear motions. As an application of this study, a mission profile capable to explore the whole plasma torus is presented. This plasma torus explorer can perform an internal "scan" of the torus itself while generating electrical power useful for loads on board the spacecraft.

AAS 09 – 241

Jovian Capture of a Spacecraft with a Self-Balanced Electrodynamic Bare Tether

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The exploration of Jupiter and the Jovian system constitutes an important challenge of planetary exploration. Among the technological obstacles to deal with, the scarcity of power is one of the most limiting factors. In recent works, electrodynamic tethers have been proposed as an efficient solution to provide power in a permanent manner. Furthermore, they are pointed out as also suitable propulsive devices to perform orbit manoeuvres in the Jovian world. In this paper, the Jupiter capture of a spacecraft using a self balanced electrodynamic tether as the propulsion system is analyzed in detail.

AAS 09 – 242

On the Thrust Capability of Electrodynamic Tethers Working in Generator Mode

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The problem of estimating the necessary conditions under which a passive electrodynamic tether (EDT) increases the orbital energy of a satellite is studied in its full generality. We derive the thrust conditions of both spinning and nonspinning EDT and the maximum achievable thrust for a generic orbit and tether attitude. After showing that in general thrust arcs are possible even when the orbital velocity exceeds the plasma velocity we show an example of EDT orbit raising starting from a low-altitude equatorial elliptic orbit around Jupiter.

AAS 09 – 243

Orbital Maneuvering With Librating and Spinning Electrodynamic Tethers

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Orbital maneuvering with electrodynamic tethers is considered using optimal control. A guidance scheme is developed that calculates the electric current as a function of the system orbital elements and tether dynamic state. The optimal current profile is determined so as to affect a desired change in the spacecraft's orbital elements. The process is repeated online in a sampled data feedback manner to enable closed-loop control of the orbital maneuver. One of the benefits of this approach is that it works for both librating and spinning tethers, and no simplifications are made in the analysis of forces on the system.

AAS 09 – 244

Saturn Power Generation with Electrodynamic Tethers in Polar Orbit

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A power generation scheme based on bare electrodynamic tethers (EDT) working in passive mode is investigated for the purpose of supplying power to scientific missions at Saturn. The system employs a spinning EDT on a low-altitude polar orbit which permits to efficiently convert plasmasphere energy into useful power. After optimizing the tether design for power generation we compute the supplied power along the orbit and the impact of the Lorentz force on the orbital elements as function of the tether and orbit characteristics. Although uncertainties in the current ionosphere density modeling strongly affect the performance of the system the peak power density of the EDT appears be greater than conventional power systems.

AAS 09 – 245

Spin-up and Deployment Control of a Tether Sling

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A tether sling holds tremendous promise as an energy storage device, permitting space transportation systems capable of injecting a large number of payloads with low incremental costs. This paper develops motor and deployment controls to go from rest to a desired final tether length and end velocity. Oscillations in the tether deployment angle are minimized in order to avoid additional tension in the tether. Open loop control laws are developed for both power unlimited and power constrained cases. For unlimited power, the time optimal mission profile dictates deployment at large angular velocities. The situation is reversed when power is constrained; spin-up and deployment time is reduced by deploying at very low angular velocities.

AAS 09 – 246

Tether Deployment Modeling for the Sounding Rocket Experiment

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A sounding rocket experiment is planned that will deploy a bare tape tether. The tether will be passively deployed in this experiment, and therefore high fidelity simulations are needed to verify the proposed mission sequence. This paper presents a model of the system for conducting deployment simulations. The model represents the tether as a discrete set of point masses connected via viscoelastic springs. The rigid body rotations of the two end bodies, together with the tether attachment point offsets are included in the simulation. High order gravity and atmospheric models are used to improve the fidelity of the numerical simulation.

SESSION 21: ATTITUDE DYNAMICS AND CONTROL 2
Chair: Ryan Park, JPL

AAS 09 – 247

Application of SDRE Method to Design a Simulator Attitude Control System

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Space missions involving automatic procedures for large angle maneuvers and control, using new non-linear control techniques, require from the satellite Attitude Control System (ACS) reliability and adequate performance. In that context, experimental validation of new equipment and/or non-linear control techniques through prototypes is the way to increase confidence in the ACS. The Space Mechanics and Control Division (DMC) of INPE is constructing a Simulation Laboratory to supply the conditions for implementing and testing satellite ACS. To set up a 3D simulator that can accommodate various satellites components; like sensors, actuators, computers and its respective interface and electronics is an important objective of DMC Lab. When designing a 3D satellite attitude control system, the designer necessarily to deal with a highly non-linear plant. Linear approximation of the plant and controller is not likely to deliver good performance for large angle maneuvers; therefore a non-linear approach must be considered. This paper presents the application of the State-Dependent Riccati Equation (SDRE) method to design a controller for a 3D satellite attitude simulator. The SDRE can be considered as the non-linear counterpart of Linear Quadratic Regulator (LQR) control technique. Practical applications are presented to address problems like presence of noise in process and measurements and incomplete state information; Kalman filter is considered as state observer to address these issues. To incorporate the non-linearities, SDRE method is also applied with filter implementation. A simulink-based model is implemented and some simulations examples are provided to demonstrate the performance of the SDRE controller with SDRE-based Kalman filter.

AAS 09 – 248
Withdrawn

AAS 09 – 249

Multiple Model Robustification of Iterative Learning and Repetitive Control Laws Including Design From Frequency Response Data

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Repetitive control (RC) and iterative learning control (ILC) aim for zero tracking error of a control system in repeating situations. RC can eliminate the influence on fine pointing equipment of slight imbalance in reaction wheels, and ILC can aim for zero error in repeated scanning maneuvers. Asking for zero error can put severe requirements on the accuracy of one's model of the system. One wants to achieve zero error in the hardware governed by the real world model and this can be different than our mathematical model used for design. Hence, stability robustness is important, asking the ILC or RC to converge to zero error in spite of imperfect knowledge of the system. Several previous publications have studied the averaging of a cost function over a distribution of possible models in order to improve stability robustness. This paper extends these works to give a more complete overview of the benefits of the approach. Three main classes of ILC are considered, and optimization criteria for each are generated so that one can perform the needed averaging. An important design approach in RC bypasses the use of a model, and directly uses experimental frequency response data. Instead of using multiple experiments to improve the frequency response information, a cost function is averaged over the data sets. Numerical investigations demonstrate for each case for ILC or RC, very substantial improvement in convergence to zero tracking error in the presence of model error.

AAS 09 – 250

Novel Three-Axis Attitude Control Algorithms for Small Satellites Using Only Magnetic Actuators

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Recently, there has been a surge of interest in small satellite missions due to low-cost launch opportunities. In particular, the feasibility of nonlinear techniques for the attitude control of small satellites using only magnetic actuators is becoming a topic of increasing interest in the literature. Since magnetic control systems are relatively lightweight, require low power and are inexpensive, they are attractive for small, inexpensive satellites in low Earth orbits. In this paper we present averaging-based feedback control laws that achieve three-axis stabilized nadir-pointing attitude. We propose nonlinear model-independent quaternion feedback laws. Two cases are considered; full state feedback that uses both attitude and angular velocity measurement and passivity-based feedback that does not require angular velocity information. Computer simulations are included to illustrate the effectiveness of the proposed control laws.

AAS 09 – 251

Planar Maneuvering of a Spacecraft With Propellant Sloshing Using Switched Feedback

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This paper studies the maneuvering control problem for a spacecraft with fuel slosh in a zero gravity environment. The propellant is modeled as a pendulum mass anchored at the center of a spherical tank. After obtaining the coupled equations of motion, linear and switched nonlinear feedback controllers are developed to achieve planar spacecraft pitch maneuvers while suppressing the slosh mode. It is shown that the linear controllers are ill-equipped to achieve the desired spacecraft attitude and transverse velocity simultaneously, especially during aggressive pitch maneuvers; while the switched nonlinear feedback controllers are superior in this regard.

AAS 09 – 252

Satellite Attitude Control Using Dissimilar Redundant Actuators

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Low Earth orbit satellites are usually equipped with magnetic torquers for momentum dumping and reaction wheels to carry out three axis attitude stabilization and control. These two different types of actuators mixed and used together to carry out slew maneuvers. The problem of allocating the control to these different types of actuators is realized using a recently developed algorithm called blended inverse. The algorithm is compared with the Moore-Penrose pseudo inverse demonstrating its success in realizing the desired maneuver while overcoming singularities.

SESSION 22: TRAJECTORY DESIGN AND OPTIMIZATION 2

Chair: Angela Bowes, NASA LaRC / Analytical Mechanics Associates

AAS 09 – 253

2 Dimensional, Fuel Optimal Earth-Moon Trajectory Design

Donghun Lee and Hyochoong Bang

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Minimum propellant, Earth-Moon trajectories are addressed in this paper. Cost function is related to fuel consumption of the spacecraft which equipped VSI engine. Two-dimensional, restricted three-body equations of motion are applied for the system dynamics, and continuously the low-thrust is used for the Earth escape trajectories, trans-lunar trajectories and Moon capture trajectories with no coast arcs. The contribution of this paper is to propose the design procedure of an optimal Earth-Moon trajectory using indirect method and also to propose the way how to obtain the Earth escape/Moon capture trajectories effectively. The propellant is quietly reduced using the VSI engine compared to previous researches where burn-coast-burn thrust sequence are used with constant specific impulse engine.

AAS 09 – 254

A Formulation of Precision Translunar Trajectory Design

Zhong-Sheng Wang

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This paper describes a new design procedure to achieve precision translunar trajectory. Good insights can be gained from the discussion of this procedure. The problem of designing a precision translunar trajectory is to find a trajectory from perigee to periselene that satisfies certain end conditions. A 3-D two-body analysis is used to find the approximate values of LAN, argument of perigee and perigee speed, then a search algorithm based on the study of contour graphs is used to find two sets of starting values, which are used in an iteration procedure to compute the values that satisfy the end conditions for periselene altitude and lunar orbit inclination.

AAS 09 – 255

Variational Equations for a Generalized Spacecraft Trajectory Model

Cesar Ocampo and J. P. Munoz

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This paper develops the variational equations associated with a spacecraft trajectory model general enough for most applications of interest. The sensitivity equations of the final state vector with respect to all the independent parameters are derived. The trajectory can have impulsive and/or finite-burn maneuvers, or mass discontinuities. The gradient expressions are derived using the state transition matrix associated with an augmented state vector, which includes the position, velocity, mass, and all other control-related quantities, such as thrust magnitude and direction. This analysis was motivated by the study of abort Moon-Earth trajectories. Examples comparing the performance of these gradients with numerically approximated ones are presented.

AAS 09 – 256

Connecting Libration Point Orbits of Different Energies Using Invariant Manifolds

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† Dept. of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado 80309, USA.

This research presents a method of using invariant manifolds to connect libration point orbits. The method presented is applicable to constructing transfers between planar or three-dimensional orbits that have different initial energies. Two deterministic maneuvers are used to connect an unstable manifold trajectory of the first orbit to a stable manifold trajectory of the second orbit. The use of the two-body eccentricity and normalized angular momentum vectors is demonstrated as a viable approach to locating unstable/stable manifold trajectory pairs with low transfer costs. A genetic algorithm is used to vary the parameters that define the transfer. Preliminary results indicate that this method produces fuel costs up to 72% less than transfer trajectories that do not employ the use of manifolds at the expense of increased transfer time. This technique is envisioned as a practical application to decreasing fuel costs and adding flexibility to mission design.

AAS 09 – 257

Optimization of Spacecraft Trajectories: A Method Combining Invariant Manifold Techniques and Discrete Mechanics and Optimal Control

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A mission design technique that uses invariant manifold techniques together with the optimal control algorithm DMOC produces locally optimal, low ΔV trajectories. Previously, invariant manifolds of the planar circular restricted three body problem (PCR3BP) have been used to design trajectories with relatively small ΔV. Using local optimal control methods, specifically DMOC, it is possible to reduce the ΔV even further. This method is tested on a trajectory which begins in Earth orbit and ends in ballistic capture at the Moon. DMOC produces locally optimal trajectories with much smaller total ΔV applied in a distributed way along the trajectory. Additionally, DMOC allows for variable flight times, leading to smaller ΔV necessary for lunar orbit insertion. Results from different Earth to Moon missions are presented in table form to show how the DMOC results fit in with actual missions and different trajectory types. The ΔV of the DMOC results are, on average, 23%-25% better than the ΔV of trajectories produced using a Hohmann transfer.

AAS 09 – 258

Analysis and Implementation of In-Plane Stationkeeping of Continuously Perturbed Walker Constellations

Jean A. Kéchichian

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The stationkeeping of symmetric Walker constellations is analyzed by considering the perturbations arising from a high order and degree Earth gravity field and the solar radiation pressure. These perturbations act differently on each group of spacecraft flying in a given orbital plane, causing a differential drift effect that would disrupt the initial symmetry of the constellation. The analysis is based on the consideration of a fictitious set of rotating reference frames that move with the spacecraft in the mean sense, but drift at a rate equal to the average drift rate experienced by all the vehicles over an extended period. The frames are also allowed to experience the J_2-precession such that each vehicle is allowed to drift in 3D relative to its frame. A two-impulse rendezvous maneuver is then constructed to bring each vehicle to the center of its frame as soon as a given tolerance deadband is about to be violated. This paper illustrates the computations associated with the stationkeeping of a generic Walker constellation by maneuvering each leading spacecraft within an orbit plane and calculating the associated velocity changes required for controlling the in-plane motions in an exacting sense, at least for the first series of maneuvers. The analysis can be easily extended to lower flying constellations, which experience additional perturbations due to drag.

AAS 09 – 259 to – 270
Not Assigned

AAS 09 – 144
From Geodesy to Satellite Geodesy (and Celestial Mechanics, and Orbit Determination, and …) (Brouwer Award Lecture)

Bob Schutz

Brouwer Award Winner, Professor and Associate Director, Center for Space Research, University of Texas at Austin, Texas 78712 USA.

Only an abstract of this presentation was available for publication.

In the third century B.C., the first known attempt to measure the radius of the Earth was accomplished with remarkable accuracy, thereby establishing the discipline of geodesy, the study of the size and shape of the Earth. With the beginning of the space age 2000 years later, satellites became an important tool of geodesy, thereby establishing a multidisciplinary area known as "satellite geodesy," with well-known participants such as Prof. Dirk Brouwer and the celebrated result that the Earth has a pear-shape. Today, the tools of satellite geodesy contribute to the study of the size, shape and mass distribution of other celestial bodies and the disciplines of celestial mechanics, orbit determination, geophysics (to name a few examples) are key elements of satellite geodesy.

BIOGRAPHY

Dr. Bob Schutz, professor of aerospace engineering at The University of Texas at Austin, was elected a fellow of the American Astronautical Society (AAS) in 2000. Schutz, who serves as associate director of the Center for Space Research at UT Austin, is a world-recognized authority on earth satellite applications, with research interests in the Global Positioning System (GPS), precision orbit and altitude determination, orbital mechanics, mission planning, and satellite geodesy. Currently he leads a team of scientists for NASA preparing to measure polar ice sheet growth and shrinkage for the next 10 to 15 years. As science team leader for the Geoscience Laser Altimeter System (GLAS), an earth-observing instrument now under development at NASA Goddard Space Flight Center, Schutz will help measure the earth's atmosphere, biosphere, and physical features from a series of satellites over a 10-15 year period, beginning with a launch in July 2001. A member of the College of Engineering faculty since 1969, Schutz received his doctorate from The University of Texas at Austin. He is a fellow of the American Geophysical Union and holds the Joe J. King Chair in Engineering at UT.

AAS 09 – 167

Industry's Obligation for Mission Success (Plenary Lecture)

Alexander C. Liang

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Only an abstract and a PowerPoint slide presentation were available to publish for this lecture. The PowerPoint slide presentation is included on the CD-ROM supplement to this volume.

With the prospect of a flat budget for both military and civilian space programs, it is incumbent upon all of us in the space industry to go the extra mile to insure that each mission is successful, not only in the contractual sense but in terms of technical achievement. We are in a very unforgiving business; one in which "one strike" and you're out. There is no second chance. The challenge for all of us is that much greater when each "mass produced" spacecraft and launch vehicle is actually unique in one form or another. Starting from concept definition, design, manufacturing, assembly, test, integration, launch and on-orbit deployment, and finally operations, we have the obligation to the nation and future generations to employ all the lessons learned, all the tools at our disposal, and the experience-based know-how to ensure 100 percent mission success. A brief description of the type of comprehensive analytical, simulation and testing/diagnostic capabilities and activities that facilitate the successful execution of each of the steps will be provided based on the author's perspective. Ensuring the use of "best practices" would, of course, enhance the overall probability of success of the eventual space mission.

See the PowerPoint slide presentation on the CD-ROM supplement to this volume for more detailed information.

BIOGRAPHY

Dr. Liang joined The Aerospace Corporation in August 1970 as a Member of the Technical Staff in the Guidance Analysis Department in Engineering Science Operations. He subsequently held positions of increasing responsibility, including Manager, Attitude Estimation and Control Section; Director, Advanced Projects Office; Principal Director, Mission Systems Analysis Office; Principal Director, Aero-Thermal and Propulsion Subdivision; Principal Director, Systems Engineering Directorate, Space Launch Operations; Chief Engineer, Space Launch Operations; General Manager, Launch Systems Engineering Division, Space Launch Operations. His last position at The Aerospace Corporation was that of General Manager, Vehicle Systems Division. Prior to joining The Aerospace Corporation, Dr. Liang was a Member of the Technical Staff at TRW Systems.

In addition to his normal responsibilities at Aerospace, he also served as Chair of the Senior Review Group for NASA's Earth Observing Systems; and was a member of the Commercial Space Transportation Advisory Committee for the FAA, Department of Transportation. He also had an assignment as a panel chair for the White House – directed Broad Area Review of the Nation's capability for assured access to space.

Dr. Liang at the age of twenty, earned two concurrent B.S.E. degrees from the University of Michigan, an M.S. degree in Engineering Science from Caltech and a

Ph.D. degree in Aerospace Engineering from the University of Southern California. He has numerous publications in the fields of navigation and guidance, optimal control, sensor design, sensor background suppression techniques, and remote sensing. He was a member of Tau Beta Pi, Phi Kappa Phi, and Sigma Xi.

Editor’s Note: Dr. Liang passed away on May 2, 2009.

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