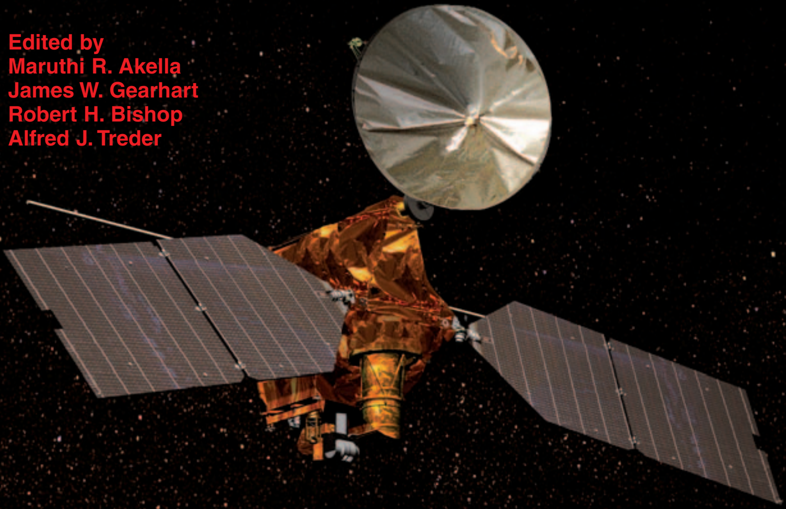
SPACEFLIGHT MECHANICS 2007

Edited by
Maruthi R. Akella
James W. Gearhart
Robert H. Bishop
Alfred J. Treder



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ADVANCES IN THE ASTRONAUTICAL SCIENCES

American Astronautical Society

SPACEFLIGHT MECHANICS 2007

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Front Cover Illustration:

An artist's impression of NASA's Mars Reconnaissance Orbiter (MRO) above the Red Planet. Launched in August 2005, MRO arrived at Mars in March 2006, where it commenced a five-month series of aerobraking maneuvers to achieve its circular mission orbit. MRO has since been providing science images of the Martian surface of unprecedented quality and resolution. Image courtesy of NASA: http://sse.jpl.nasa.gov/multimedia/gallery/MRO.jpg

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FOREWORD

This volume is the seventeenth 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 II of the hard copy volume lists proceedings available through the American Astronautical Society.

Spaceflight Mechanics 2007, Volume 124, *Advances in the Astronautical Sciences*, consists of two parts totaling about 2,200 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 second 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 2007 appears as Volume 127, *Advances in the Astronautical Sciences* (Including CD ROM). This publication presents the complete proceedings of the AAS/AIAA Spaceflight Mechanics Meeting 2007.

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

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

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

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

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

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

Spaceflight Mechanics 2000, Volume 106, *Advances in the Astronautical Sciences*, Eds. C.A. Kluever et al., 1704p, two parts.

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

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

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

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

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

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

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

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

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

Robert H. Jacobs
Series Editor

PREFACE

The 17th Annual Space Flight Mechanics Meeting was held from 28 January through 01 February 2007 in Sedona, Arizona at the Hilton Sedona Resort & Spa. The conference was co-sponsored by the American Astronautical Society (AAS) and the American Institute of Aeronautics and Astronautics (AIAA), and it was organized by the AAS Space Flight Mechanics Technical Committee and the AIAA Astrodynamics Technical Committee. Registered attendance numbered approximately 200, consisting of engineers, scientists, and mathematicians from various organizations in government, the military services, industry, and academia.

There were 121 technical papers presented in 22 sessions on the following topics: orbital dynamics and perturbations; orbit determination and tracking; trajectory design and optimization; spacecraft guidance, navigation, and control; satellite constellations and formation flying; Earth and planetary missions; libration point trajectories; atmospheric density modeling; tethered satellites; solar sails; space debris and planetary defense; and attitude determination, dynamics, and control.

The conference also included several special events. On Monday evening, the 2007 AAS Dirk Brouwer Award recipient, Dr. N. X. Vinh, presented his lecture entitled "A Unified Theory on Thrust and Aerodynamics Control in Hypersonic Flight." On Tuesday morning, Carolyn Shoemaker of the US Geological Survey presented her Plenary Session Lecture entitled "NEO Detection and Deflection," in which she discussed the detection and deflection of Near Earth Objects and what could be done to reduce the probability of their collision with Earth. Finally, on Tuesday evening, we visited the Lowell Observatory in Flagstaff, Arizona. Although the cloud cover and snowfall precluded any astronomical observations, it was fascinating to see the historic Clark Refracting Telescope used by Percival Lowell for his studies of the planet Mars.

A Workshop on "Doing Orbital Mechanics with Mathcad" was hosted on Wednesday evening by Roger Mansfield of Astronomical Data Service. The participants gained hands-on experience in using the Mathcad software to develop and execute computational algorithms from the fields of dynamical astronomy and astrodynamics.

A Workshop presenting the methods and results from the 2nd Global Trajectory Optimisation Competition was held on Thursday. This year's competition, which was organized by the Outer Planets Mission Analysis Group of the Jet Propulsion Laboratory, involved the trajectory optimization of a "Grand Asteroid Tour," for which a hypothetical spacecraft employing electric propulsion must launch from the Earth and rendezvous with four asteroids, using an objective function that rewards low propellant consumption and low total flight time. The winning team this year was from the Politecnico di Torino in Italy.

The editors of these proceedings would like to extend their gratitude to the following Session Chairs who helped make this conference a success: Jeff Beck, Dennis Byrnes, Al

Cangahuala, Russell Carpenter, Prasun Desai, Tom Eller, Michael Gabor, Bob Glover, Felix Hoots, Richard Longman, Alan Lovell, Don Mackison, Craig McLaughlin, Beny Neta, Frederic Pelletier, Ron Proulx, Paul Schumacher, John Seago, Jon Sims, David Spencer, Tom Starchville, and Yunjun Xu.

We would also like to express our thanks to the Orbital Sciences Corporation for the cover design and printing of the conference programs.

Finally, many thanks to Shannon Coffey for his continual support and assistance with the Abstract Administration Website, which greatly facilitated the operation of this conference.

Maruthi R. Akella
The University of Texas at Austin
AAS Technical Chair

James W. Gearhart
Orbital Sciences Corporation
AIAA Technical Chair

Robert H. Bishop
The University of Texas at Austin
AAS General Chair

Alfred J. Treder
Barrios Technology
AIAA General Chair

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WITHDRAWN OR NOT ASSIGNED

AAS 07 – 109, 122, 123, 138, 139, 142, 144, 149, 152, 164, 168, 180, 184, 186, 187, 195, 204, 205, 214, 219, 222, 225, 230, 231, 233, 236, 238, 239 249 to 250

SESSION 1: ATTITUDE ESTIMATION
Chair: Richard Longman, Columbia University

AAS 07 – 100

Accurate On-Ground Attitude Determination for the GAIA Mission Using Kalman Smoother

Malak A. Samaan and Stephan Theil, University of Bremen

In this paper, we design and analyze algorithms representing the operational mode of the on-board Attitude Determination System (ADS) for the GAIA mission using the on-board measurements sensor data and the Kalman filtering. Also, we design and select the best on-ground attitude determination algorithm that gives the most accurate attitude knowledge using the Kalman filter and the smoothing procedure. The principal feature of the GAIA astrometry mission is a highly stable payload consisting of two scientific instrument telescopes with one big focal plane containing an array of 106 CCDs. In order to achieve these highly stable requirements, the GAIA spacecraft should have very accurate attitude determination sensors and also very accurate control actuators.

AAS 07 – 101

A Batch Filter Based on the Unscented Transformation and Its Applications to Spacecraft Attitude Determination

Kyoung-Min Roh, Sang-Young Park, Eun-Seo Park and Kyu-Hong Choi,
Yonsei University

The present paper provides a method for precision attitude determination of spacecraft using the Unscented Transformation as a batch processor. The goal of this study is to establish the batch processor without any linearization approximation. A new algorithm implementing the Unscented Transformation is used for precision attitude determination of spacecraft at epoch time (not successive time) using measurements obtained during fixed time span. The performance of the precision attitude determination method is tested and compared with that of the Bayesian batch processor. The results are also compared with those achieved sequentially using the Unscented Kalman Filter and the Extended Kalman Filter.

AAS 07 – 102

Robustness and Accuracy of the QUEST Algorithm

Yang Cheng, University of Buffalo; Malcolm D. Shuster, Acme Spacecraft Co.

Markley and Mortari have reported recently that the QUEST algorithm has problems of robustness and accuracy, unlike Wahba-problem-based attitude estimation algorithms which use the FOAM form of the characteristic equation for the maximum overlap eigenvalue, developed by Markley. We show that the bad case presented by Markley and Mortari is extremely bizarre and not attainable with existing sensors, not to mention an extraordinarily poor design for an attitude determination system. Furthermore, the so-called robustness and accuracy problem vanishes completely if a trivial rearrangement of terms is made in the corresponding QUEST characteristic polynomial. The inverse rearrangement of terms causes equally bad performance in the algorithms of Markley and Mortari.

AAS 07 – 103

Some Directions in Spin-Axis Attitude

Sergei Tanygin, Analytical Graphics, Inc.; Malcolm D. Shuster, Acme Spacecraft Co.

Spin-Axis attitude estimation has much in common in its techniques with three-axis attitude estimation. These similarities are exploited to gain a greater appreciation of the workings of both. Several techniques for spin-axis attitude estimation are examined. We find, in particular, that unconstrained estimation followed by brute-form normalization yields a significantly poorer result than do methods in which the normalization is maintained to at least second order throughout the estimation process. This has obvious consequences for practitioners of unconstrained quaternion estimation. The connection between constraint errors and correlations is examined.

AAS 07 – 104

The Many TRIAD Algorithms

Sergei Tanygin, Analytical Graphics, Inc.; Malcolm D. Shuster, Acme Spacecraft Co.

The TRIAD algorithm has many variations, which yield attitude estimates for two direction measurements of very different accuracy. We examine a generalized TRIAD algorithm of which the different algorithms become different examples. Within this framework we examine the attitude estimate-error covariance matrices. One example, in particular, yields the same accuracy as the QUEST algorithm for two vectors.

AAS 07 – 105

The Speed of Attitude Estimation

Yang Cheng, University at Buffalo; Malcolm D. Shuster, Acme Spacecraft Co.

The operation counts and execution times for the fast batch attitude estimators have been studied extensively and in great detail. There turns out to be no unambiguous fastest optimal attitude estimation algorithm, although a small group is found to be faster than the rest. The various factors effecting the determination of execution speed in typical analytical studies and in actual mission implementation are examined.

AAS 07 – 106

The Two Sun-Cones Attitude Determination Method

Jozef C. van der Ha, Kyushu University

Spin-stabilization offers a straightforward but robust attitude control. For Earth-orbiting satellites, attitude determination can be done by Sun and Earth sensor measurements. For deep space missions, however, valid Earth sensor measurements are not available. The paper presents a technique for the determination of the spin axis orientation using only Sun sensor data, collected at two different instants of time. The spin axis attitude follows from the intersection of the two Sun angle cones. The application of the TSC method was validated using actual in-orbit Sun sensor measurements of CONTOUR. The results show that an attitude accuracy of 1 deg can be reached after an interval of only a few hours and 0.1 deg can be achieved after a 2-days interval.

SESSION 2: SATELLITE CONSTELLATIONS AND FORMATION FLYING I
Chair: Ron Proulx, Draper Laboratory

AAS 07 – 107

Algorithms for Safe Spacecraft Proximity Operations

David E. Gaylor and Brent William Barbee, Emergent Space Technologies, Inc.

Future missions requiring in-space servicing, repair, inspection, or rendezvous and docking need algorithms for safe, autonomous proximity operations. Algorithms for relative navigation, maneuver planning and execution, and safe separation and circumnavigation trajectory design are presented. The algorithms rely on safe, natural motion trajectories and covariance information from relative navigation to minimize the probability of collision. The algorithms are described in the context of a space inspection mission where two attached spacecraft separate and one circumnavigates the other. These algorithms can also be applied to a variety of rendezvous or other proximity operations missions, whether autonomous or manually operated.

AAS 07 – 108

Analytical Solution to Optimal Relocation of Satellite Formation Flying in Arbitrary Elliptic Orbits

Han-Cheol Cho, Sang-Young Park, Sung-Moon Yoo, and Kyu-Hong Choi,
Yonsei University

This paper presents a general analytic solution to reconfiguration problem for satellite formation flying in an arbitrary eccentric orbit. Fixing the initial and final true anomalies as boundary conditions, fuel-optimal problem can be formulated for reconfiguration of satellite formation. Three-orthogonal thrusts are used and each of them is represented by the Fourier series. It is assumed that thrusters are of low levels, thus thrusters are fired during a significant fraction of an orbital period throughout the maneuver. An analytic optimal solution is derived for the magnitude and direction of thrust as function of true anomaly. A closed-form solution to the optimal relocation problem is found, and the solution will be very useful for designing a feedback controller for satellite formation flying in general elliptical orbit.

AAS 07 – 109
Withdrawn

AAS 07 – 111

Periodic Relative Motion Near a Keplerian Orbit With Full Approach: Application to Formation Flight

S. J. Li and F. Y. Hsiao, Tamkang University

This paper presents a new methodology for determining relative motion initial conditions for periodic motion in the vicinity of a Keplerian orbit, whose dynamics is described by the Tschauner-Hempel Equation. After briefly reviewing the classical approach, we propose with a new methodology to derive spacecraft relative dynamics with full solutions of the two-body problem. Our works avoid solving differential equations, and provide a more precise approximation. A nominal circular orbit is selected as the numerical simulations to verify our results. This result can be applied to the formation of small/micro satellites, and used for lowering down the fuel.

AAS 07 – 112

Spacecraft Collision Avoidance Using Coulomb Forces With Separation Distance Feedback

Shuquan Wang and Hanspeter Schaub,
Virginia Polytechnic Institute and State University

A 2-spacecraft collision avoidance problem is discussed. The spacecraft are assumed to be floating freely in deep space. A control strategy using cluster internal Coulomb forces is developed to prevent collision of the two spacecraft. The control law is designed to keep the distance greater than a constraint value, and meanwhile, the control is also committed to keep the departure relative kinetic energy at the same level with the approach kinetic energy. Further, this strategy only requires measurements of the separation distances. With the presence of charge saturations of spacecraft, it's not guaranteed that the collision can always be prevented. Conditions under which a collision can be avoided are discussed by formulating the charged spacecraft relative motion using concepts of orbital mechanics.

AAS 07 – 113

Spacecraft Formation Flying and Reconfiguration With Electrostatic Forces

Vaios Lappas, Chakravarthini Saaj and Dave Richie, Surrey Space Centre, University of Surrey; Mason Peck and Brett Streetman, Cornell University;
Hanspeter Schaub, Virginia Polytechnic Institute and State University

Natural charging due to ambient plasma and the photoelectric effect can produce Coulomb forces of 10-1000 mN, which could disturb the configuration of swarms of spacecraft in formations close enough that Debye shielding is negligible. Even in the presence of Debye shielding, charged spacecraft interact with the planetary magnetosphere and generate Lorentz forces, which can also disturb precision formations. The magnitude of these disruptive intersatellite Coulomb forces is comparable to typical ion thrusters proposed for spacecraft formation flying. We propose to develop an efficient hybrid propulsion system combining Coulomb forces, Lorentz forces, and standard electric thrusters for formation flying of the order of tens of meters in geostationary or other high Earth orbits.

AAS 07 – 201

Non-Parametric Collision Probability for Low-Velocity Encounters

J. Russell Carpenter, NASA Goddard Space Flight Center

An implicit, but not necessarily obvious, assumption in all of the presently used techniques for assessing satellite collision probability is that the relative position uncertainty is perfectly correlated in time. If there is any mis-modeling of the dynamics in the propagation of the relative position error covariance matrix, time-wise de-correlation of the uncertainty will increase the probability of collision over a given time interval. The paper gives some examples that illustrate this point. This paper argues that, for the present, Monte Carlo analysis is the best available tool for handling low-velocity encounters, and suggests some techniques for addressing the issues just described. One proposal is the use of a non-parametric technique that is widely used in actuarial and medical studies.

SESSION 3: TRAJECTORY DESIGN AND OPTIMIZATION I
Chair: Jon Sims, Jet Propulsion Laboratory

AAS 07 – 114

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

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

The vehicle of study is the Common Aero Vehicle. Of military interest is the ability to autonomously mission plan multiple intermediate waypoints and no-fly zones, while ensuring a flyable trajectory. The cost function is flight time due to time-critical targets. Due to hypersonic velocity during reentry the turn radii are significant compared to the overall range from initial point to final target. The research herein demonstrates an analytical geometric trajectory optimization technique and compares it to numerically derived results. The result converges to the optimal solution with less computational time and assurance that a solution exists.

AAS 07 – 115

A Space Mission Automaton Using Hybrid Optimal Control

Christian M. Chilan and Bruce A. Conway, University of Illinois

A modern space mission is composed of several events such as impulsive maneuvers, thrust arcs, and planetary flybys. Traditionally, a mission planner would develop a structure for the mission using categorical variables, and then find the best spacecraft trajectory by solving a continuous optimal control problem. A problem of this type is known as a hybrid optimal control problem (HOCP). A recent approach to solving HOCP's has the potential to automate the mission planning process. The method uses two nested loops. In this work, we introduce genetic algorithms and direct transcription with nonlinear programming as methods of solution for the outer-loop and inner-loop problems respectively. A multiple asteroid interception mission is solved as an example of the method.

AAS 07 – 116

Orbital Maneuver Optimization Using Time Series

James D. Thorne, Institute for Defense Analyses

Orbital maneuver optimization is traditionally accomplished using either classical calculus of variations techniques or direct numerical sampling. The availability of explicit time series solutions to the Lambert orbit determination problem will allow the total delta-v for a series of orbital maneuvers to be expressed as an algebraic function of only the individual transfer times. The delta-v function may then be minimized for a series of maneuvers by finding the optimal transfer times for each orbital arc. Results are shown for the classical example of the Hohmann transfer, as well as an interplanetary fly-by mission to the asteroids Pallas and Juno.

AAS 07 – 117

Path-Constrained Optimal Trajectory Design for the Upper Stage of a Vertical Takeoff Vertical Landing Launch Vehicle

Yunjun Xu, University of Oklahoma

A hybrid optimization methodology is used for finding the path constrained optimal trajectory of the launch vehicle's upper stage. This method takes advantage of both direct and indirect approaches. In the direct transcript portion, the Trapezoid method and the Legendre-Gauss-Lobatto pseudo-spectral method are applied and compared. In the indirect transcript portion, four homotopies plus the "heaviside" method are combined in finding the optimal solution. Upper stage separation speed and altitude from the first stage of the launch vehicle are used as the design parameters. Numerical examples demonstrate the effectiveness of this hybrid algorithm.

AAS 07 – 118

Planetary Moon Cycler Trajectories

Ryan P. Russell and Nathan J. Strange, Jet Propulsion Laboratory

Free-return cycler trajectories repeatedly shuttle a spacecraft between two bodies using little or no fuel. Here, the cycler architecture is proposed as a complimentary and alternative method for designing planetary moon tours. Previously applied enumerative cycler search and optimization techniques are generalized and specifically implemented in the Jovian and Saturnian systems. The brief synodic periods contribute to the existence of hundreds of ballistic cycler geometries. Many of the idealized model solutions are found to remain ballistic in more realistic models. Of the most promising applications is the Titan-Enceladus system where recent discoveries by Cassini have thrust both bodies into the science spotlight.

AAS 07 – 119

POST2 End-to-End Descent and Landing Simulation for the Autonomous Landing and Hazard Avoidance Technology Project

Jody L. Fisher and Scott A. Striepe, NASA Langley Research Center

The Program to Optimize Simulated Trajectories II (POST2) is used as a basis for an end-to-end descent and landing trajectory simulation that is critical in determining the design and integration capability of lunar descent and landing-system models and lunar environment models for the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project. This POST2-based ALHAT simulation provides descent and landing simulation capability, along with the data necessary to design and operate a landing system for lunar-landing success. This paper presents the development and model validation of the POST2-based end-to-end trajectory simulation used for the testing, performance and evaluation of ALHAT project models.

AAS 07 – 120

The Streamlined and Complete Set of the Nonsingular J2-Perturbed Dynamic and Adjoint Equations for Trajectory Optimization in Terms of Eccentric Longitude

Jean A. Kéchichian, The Aerospace Corporation

The complete set of the dynamic and multipliers differential equations for a non-singular set of equinoctial elements where the eccentric longitude stands for the sixth orbital element are derived in a more straightforward and streamlined manner as compared to a previous derivation. Furthermore, this formulation is used to derive the adjoint differential equations by accounting for the secular first order effect of the zonal harmonic J2. The present formulation removes the need to solve for Kepler’s transcendental equation at each integration step, a need that is inevitable when the mean longitude formulation is used.

SESSION 4: ORBIT DETERMINATION AND TRACKING I

Chair: Beny Neta, Naval Postgraduate School

AAS 07 – 121

Orbit Determination and Prediction for Low Earth Satellites Using a Single Pass of Observation Data

Kyle T. Alfriend, Texas A&M University;
Chris Sabol and Jill Tombasco, Air Force Research Laboratory

This report provides the development of a simplified covariance model for predicting the along-track error uncertainty and error uncertainty growth rate for the single-pass, orbit determination and prediction problem for low Earth satellites. The model is validated using simulation and real data cases. Lastly, the model is used to generalize single pass orbit prediction results using angles-only, range-only, range and angles, and range and range-rate data. The results indicate the most accurate solutions occur using a combination of range and angles data.

AAS 07 – 122
Withdrawn

AAS 07 – 123
Withdrawn

AAS 07 – 125

The Orbit Determination Tool Kit (ODTK), Version 5

Richard S. Hujsak, James W. Woodburn, and John H. Seago, Analytical Graphics, Inc.

Orbit Determination Tool Kit is commercial software for geocentric spacecraft-orbit determination and analysis from Analytical Graphics, Inc. Key features include a tracking-data simulator, an optimal (Kalman-like) sequential filter, and a sequential fixed-interval smoother. Functionality includes autonomous measurement editing, customizable reporting and graphing, simultaneous multiple-satellite estimation, and modeling of time-varying system biases. Version 5 of the Tool Kit adds two significant capabilities: a broad operational capability for maintaining global-navigation satellite systems such as the US Global Positioning System, and the ability to refine location estimates for poorly known emitters using time-difference-of-arrival and frequency-difference-of-arrival measurements.

AAS 07 – 126

TLE or Not TLE? That is the Question

David Finkleman, Center for Space Standards and Innovation

This paper reports orbit data exchange standards, messages, and formats developed under the auspices of the International Organization for Standardization, the AIAA, and the CCSDS. The goals are backward compatibility with Two Line Element Sets (TLE), congruence with the international standard for deep space Orbit Data Messages, use of Extensible Markup Language (XML) space ontologies, and incorporating elements of information essential for propagating estimated satellite states. This paper will describe the proposed content of the orbit data transfer standard, explain how data element choices were made, and infer the technical consequences of having a standard.

AAS 07 – 127

Validation of SGP4 and IS-GPS-200 Against GPS Precision Ephemerides

T. S. Kelso, Center for Space Standards and Innovation

Many applications use the NORAD SGP4 orbital model for predicting satellite ephemerides and often these applications require knowledge of the errors associated with those predictions. Unfortunately, the SGP4 orbital data, in the form of two-line element (TLE) sets, does not provide any kind of accuracy information. Some approaches have been published which purport to estimate these errors by performing consistency or abutment checks, but they do not validate their assumptions or provide any validation by comparison to high-accuracy ephemerides. This paper will show the suitability of these approaches by comparing SGP4 ephemerides to precision ephemerides available for the GPS constellation.

SESSION 5: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL I
Chair: Frederic Pelletier, Jet Propulsion Laboratory

AAS 07 – 128

Accelerometer Evaluation for the Mission to Jupiter

Sergei A. Jerebets, Jet Propulsion Laboratory

Due to severe radiation environment of the Jovian system, the mission to Jupiter inherently presents a significant technical challenge to Attitude Control System design since navigation sensors must survive and function properly to reliably maneuver the spacecraft throughout the mission. Different accelerometer technologies and their critical performance characteristics are discussed, compared and evaluated to facilitate a choice of appropriate accelerometer (within inertial measurement unit or as a stand-alone sensor) to operate in a harsh Jovian environment to assure mission success.

AAS 07 – 129

Adaptive Entry Navigation Using Inertial Measurements

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

The application of a multiple model adaptive estimator architecture to entry navigation during the highly dynamic hypersonic pre-parachute deploy phase is investigated. The entry navigation filter design is approached by processing accelerometer data in an extended Kalman filter as external measurements, rather than the more traditional approach of processing them in the propagation phase (dead-reckoning). The high uncertainty associated with the Martian atmospheric density is handled with multiple dynamic models comprising a filter bank The proposed filtering architecture is compared to the dead-reckoning process.

AAS 07 – 130

An Experimental Validation of Spacecraft Attitude and Power Tracking With Variable Speed Control Moment Gyroscopes

Dongwon Jung and Panagiotis Tsiotras, Georgia Institute of Technology

Variable Speed Control moment gyros (VSCMGs) distinguish themselves from the conventional CMGs by having extra degrees of freedom to control the wheel spin rates in addition to the gimbal angles. Thus, they can be adopted to achieve additional objectives, such as energy storage, as well as attitude control. VSCMGs are ideal for integrated power/attitude control systems (IPACS). The gimbal rates of the VSCMGs can be used to provide the attitude control torque, whereas the wheel accelerations can be used for both attitude and power tracking. Several control laws for simultaneous attitude and power tracking have been proposed in the literature. In this paper we experimentally validate an IPACS control law proposed in our previous work using a realistic 3-dofspacecraft simulator.

AAS 07 – 131

Chattering Free Robust Control for Nonlinear Systems

Yunjun Xu, University of Oklahoma

A new design which fully uses the sliding manifold information is proposed to achieve a feedback chattering free nonlinear control law. The guaranteed asymptotic stability is proven using the Lyapunov second theorem and the invariance principle. An explicit time varying feedback gain derived according to the global stability and sliding manifold variations is proved to be uniquely solvable based on the Perron–Frobenius theorem. The proposed nonlinear controller which relies on the nominal system maintained the advantages of the conventional variable structure and boundary layer control. In the mean time, it will not compromise the steady state error. Theoretical and numerical studies show that the proposed control methodology is superior to traditional variable structure control in terms of smooth transient performance and saturation protection.

AAS 07 – 132

Control of Science Orbits About Planetary Satellites

Marci Paskowitz Possner, GMV Space Systems Inc;
Daniel J. Scheeres, University of Michigan

In this paper, control issues for science orbits about planetary satellites are investigated. The science orbits have low altitudes, near-polar inclinations and follow the stable and unstable manifolds of frozen orbits. The effect of orbit uncertainty caused by initial position errors is studied, and criteria are identified to ensure the desired behavior for the orbits. Two schemes to control a planetary satellite orbiter are developed: a) given the terminal conditions of a science orbit, redesign a new science orbit and execute a low-cost transfer to it, b) return the spacecraft to its nominal trajectory via a two-sequence set of maneuvers.

AAS 07 – 133

Flight Performance Analysis of a High Accuracy Inter-Satellite Ranging Instrument

Jeongrae Kim, Hankuk Aviation University

The NASA/DLR GRACE mission is a dedicated gravity mapping mission using two low earth satellites. The satellites, launched in 2002, are currently operational and producing new Earth gravity models. The flight data from the K-band inter-satellite ranging system (KBR), which is the key instrument of the GRACE, has been analyzed in order to validate the instrument modeling and to improve instrument calibration techniques. Comparison with GPS measurements is performed and possible un-modeled error sources are discussed.

AAS 07 – 134

Onboard Trajectory Determination for Mars Approach Using Monte Software Components on Electra Spare Sparc Capacity

Courtney B. Duncan, Jet Propulsion Laboratory

"Access to all of Mars" is a top priority for Mars payload delivery. An important component of this capability is improved state knowledge during the late phases of flight from Earth to Mars. This paper describes work in progress to utilize spare processing capacity in the JPL-developed Electra software defined radio to compute in-situ trajectory from radio and other onboard measurements. Some software for this real-time application is ported from the JPL-developed Monte navigation tool suite that is primarily intended for ground-based processing. Software issues that result, such as effects on performance and footprint, are discussed.

AAS 07 – 135

Optimal Control of Uncertain Trajectories Using Continuous Thrust

Eric D. Gustafson and Daniel J. Scheeres, University of Michigan

The optimal control of a nonlinear system is studied near an unstable equilibrium point. Uncertainty in the initial conditions is assumed to have a Gaussian distribution, then this uncertainty is propagated forward in time under optimal control. This process of measuring the state with a given uncertainty, then applying optimal control is repeated with a fixed time-between-measurements. For hyperbolically unstable systems, we show that there is an optimal value for the time-between-measurements. We then apply the method to control a spacecraft in the vicinity of a relative equilibrium point in the circular restricted 3-body problem (CR3BP) using a semi-analytical framework.

SESSION 6: ORBIT DYNAMICS AND PERTURBATIONS I
Chair: Bob Glover, AT&T

AAS 07 – 136

A Complex Exponential Keplerian Universal Solution

Troy A. Henderson and John L. Junkins, Texas A&M University

A Complex Exponential Keplerian Universal (CEKU) solution has been developed as a solution to the classical universal two-body problem. This formulation takes advantage of regular exponential functions with complex arguments. The eigenstructure of the problem is exploited and the solutions that follow are completely real numbers. This development follows the classical development presented by Battin.

AAS 07 – 137

Orbital Maneuvers Using a Close Approach in a Return Passage by the Main Body

D. P. S. Santos, A. F. B. A. Prado, and E. M. Rocco,
National Institute for Space Research (INPE), Brazil

The objective of this paper is to study space maneuvers that consist in a spacecraft leaving one celestial body and going back to this same body, using this return passage to perform a Swing-By with the mother planet to change its velocity, energy and angular momentum. This is called here "Swing-By Maneuvers using Consecutive Collision Orbits". During this approach, the space vehicle places itself in an orbit different from the initial one, for the interest of the mission.

AAS 07 – 138
Withdrawn

AAS 07 – 139
Withdrawn

AAS 07 – 140

Orbital Dynamics of Laser-Propelled Space Vehicles in Low-Earth Orbit

Hiroshi Yamakawa, Kyoto University;
Ikkoh Funaki, Japan Aerospace Exploration Agency

This paper investigates the dynamics of an active space vehicle or a passive object around an orbiting station, assuming a laser-propelled system from the orbiting station in low-earth orbit. The linear rendezvous equations, Clohessy-Wiltshire equations, are used for the analysis. Periodic trajectories around the orbiting laser station were investigated and a first-order approximate solution was given, which provides sufficient analogy with numerically integrated trajectory in terms of amplitude and frequency variation under short flight time condition.

AAS 07 – 141

Regular Representation of the First- and Second-Order Gradients of the Geopotential

Stefano Casotto, University of Padua, Italy

The derivatives of the geopotential expressed in Spherical Harmonics are known to be singular at the poles, and subject to the of loss of significant digits when computed in the high-latitude regions. It is shown here that this problem can be removed by judicious choice of identities and recurrence relations to regularize certain apparently singular expressions involving the Associated Legendre Functions which appear in the formulation. The formulation of the geopotential and its first two derivatives applicable to the polar axis is also provided.

AAS 07 – 142
Withdrawn

AAS 07 – 143

Design Using Gauss' Perturbing Equations With Applications to Lunar South Pole Coverage

K. C. Howell, D. J. Grebow and Z. P. Olikara, Purdue University

The three-body problem is formulated in terms of osculating elements using Gauss' perturbing equations. The state-transition matrix is available and is, thus, a mechanism for the computation of semi-elliptical periodic orbits. A method for moving along the tangent subspace to compute families of periodic orbits is posed. The method is applied to the Earth-Moon system, where families of periodic orbits are calculated possessing the characteristics desirable for lunar south pole coverage.

AAS 07 – 144

Withdrawn

SESSION 7: SPACE DEBRIS AND PLANETARY DEFENSE
Chair: Jeff Beck, Northrop Grumman Corporation

AAS 07 – 145

Hovering Control of a Solar Sail Gravity Tractor Spacecraft for Asteroid Deflection

Bong Wie, Arizona State University

A Solar Sail Gravity Tractor (SSGT) spacecraft is proposed as a viable option for deflecting a certain class of near-Earth asteroids such as highly porous rubble piles rather than solid monolithic bodies. Solar sails are large, lightweight reflectors in space that are pushed by sunlight. The SSGT spacecraft concept is simply based on the so-called Gravity Tractor (GT) for towing asteroids by using gravity as a towline, proposed by Lu and Love in the 10 November 2005 issue of Nature. It further exploits the propellantless nature of solar sails, and consequently its advantage over a GT spacecraft propelled by ion engines is its possible longer mission life times (> 5 years) with a larger propellantless Delta-V capability.

AAS 07 – 146

New Star Catalogs and New Applications

Dave G. Monet, U.S. Naval Observatory

The current generation of star catalogs offers system designers accuracies as good as 20 milliarcseconds, wavelengths from blue to infra-red, and brightnesses from 1st to 20th magnitude. Several new surveys are in progress (or being planned) that will improve the accuracies to almost 1 milliarcsecond and extend the faint limit to 22nd magnitude and beyond. Whether for traditional star trackers or for in-frame metrics, these catalogs can be used to improve existing applications or as the basis for new ones. A survey of the existing and planned catalogs will be given, and examples of high-accuracy applications will be presented.

AAS 07 – 147

Optimal Deflection of Earth-Crossing Objects Using a Power Limited Spacecraft

Young-Joo Song, Sang-Young Park, and Kyu-Hong Choi, Yonsei University

An optimal deflection method for Earth-Crossing Objects (ECOs) is formulated for a power limited spacecraft. To avoid the Earth impact, ECO's momentum is continuously changed using a power limited laser ablation system carried by a conceptual future spacecraft. The optimal operating duration and deflection angle variation history are estimated as control variables for various ECOs. Effects on the optimal operating duration and operation angle history are also analyzed as ECO's orbital elements and the power levels of the ablation tool vary. The timing of the operation start is very important and is preferred to be as early as possible. This method is more practical because there will be ECO's fragmentation or unexpected orbital motions, and most spacecraft can provide only limited energy.

AAS 07 – 148

Review of Conjunction Probability Methods for Short-Term Encounters

Salvatore Alfano, Center for Space Standards and Innovation

The paper discusses current methods for computing collision probability between space-borne objects. The early formulations of spacecraft collision were based on the Poisson distribution and used concepts from the kinetic theory of gases in which the molecules move in straight lines and their number density is statistically uniform. Current formulations are more realistic, being based on the Gaussian distribution and the concept of covariances which can be obtained from orbit determination. In broad general terms and in chronological order, there are four main categories to classify the current models. These are the Foster (1992), Chan (1997), Patera (2000) and Alfano (2002).

AAS 07 – 149
Withdrawn

SESSION 8: SATELLITE CONSTELLATIONS AND FORMATION FLYING II
Chair: David Spencer, Pennsylvania State University

AAS 07 – 150
A Greedy Random Adaptive Search Procedure for Optimal Scheduling of P2P Satellite Refueling

Atri Dutta and Panagiotis Tsiotras, Georgia Institute of Technology

All studies of peer-to-peer (henceforth abbreviated as P2P) satellite refueling so far assume that all active satellites return back to their original orbital positions after undergoing fuel exchanges with the passive satellites. In this paper, we remove this restriction on the active satellites, namely, we allow the active satellites to interchange orbital slots during the return trips. We formulate the problem as a three-index assignment problem in a tripartite constellation graph. We use a greedy random adaptive search procedure (GRASP) to determine the optimal P2P refueling schedule between the active and the passive satellites. It is shown that the proposed methodology leads to considerable fuel reduction over the baseline P2P refueling strategy.

AAS 07 – 151
A Network Flow Formulation for an Egalitarian P2P Refueling Strategy

Atri Dutta and Panagiotis Tsiotras, Georgia Institute of Technology

A variation of the P2P strategy, known as egalitarian P2P (E-P2P) refueling strategy, relaxes the restriction on the active satellites to return to their original orbital slots after undergoing the fuel transactions. The E-P2P refueling problem can be formulated as a three-index assignment problem on an undirected tripartite constellation graph, which can be solved using, say, a Greedy Random Adaptive Search Procedure (GRASP). In this paper we consider again the E-P2P problem, which we formulate as a minimum cost flow problem on a directed graph, along with some additional constraints. The solution of the corresponding integer program yields the optimal satellite assignment.

AAS 07 – 152
Withdrawn

AAS 07 – 153

Control of Interferometric Satellite Arrays for (*u*,*v*) Plane Coverage in Multi-Body Regimes

Lindsay D. Millard and Kathleen C. Howell, Purdue University

Satellite imaging formations have numerous applications in the future of space exploration. Therefore, control of these arrays in multi-body regimes is critical. An optimization problem to minimize fuel usage while maximizing an image metric is formulated in the circular restricted three-body problem. This image metric is derived based on ideal mission-specific coverage of the (*u, v*) plane. An augmented Lagrange Multiplier method is employed to formulate the optimization problem, which is numerically solved for formations of satellites moving near halo orbits. Image reconstruction is demonstrated for different mission parameters, such as formation size and baseline length.

AAS 07 – 154

Control of Spacecraft Formation About a Near-Circular Orbit

F. Y. Hsiao and S. J. Li, Tamkang University, Taiwan

This paper investigates a methodology of control law design for formation flight of spacecraft about a Keplerian near-circular orbit. We first introduce the Tschauner-Hempel Equation, describing the relative motion about a Keplerian orbit, and briefly review its solutions. The "local time approximation", shown well-performed in controlling the spacecraft formation about halo orbits, is then proved applicable to our problems. This approximation enables us to design a position-and-velocity feedback under "locally" time-invariant circumstances. Among all possible choices, we propose a control law that can duplicates a "scaled" nominal trajectory for the relative motion. Numerical simulations are presented to verify our results.

AAS 07 – 155

Effects of Orbital Perturbations on the Performance of a Relative Navigation Filter for High Earth Orbits

Christopher Lane and Penina Axelrad, University of Colorado

This paper extends previous analysis on relative navigation in high Earth orbits to include the impact of unmodeled dynamics on filter performance. A relative navigation filter is developed that estimates relative Keplerian elements by processing singly differenced GPS pseudorange measurements. The dynamic model and filter performance are presented for medium and high Earth orbits with limited measurement availability. The focus is on evaluating the effect of higher-order gravity terms, solar radiation pressure, the third-body effects of the Sun and Moon, and atmospheric drag on estimation accuracy. Relative semi-major axis accuracy of 0.81 m and relative position accuracy of 0.89 m are obtained for vehicles separated by 10-170 km in HEO using GPS measurements only.

SESSION 9: TRAJECTORY DESIGN AND OPTIMIZATION II
Chair: Prasun Desai, NASA Langley Research Center

AAS 07 – 156

A Path Based Approach for Optimizing Low-Thrust Interplanetary Trajectories

Prashant Patel, Daniel Scheeres, Alec Gallimore and Thomas H. Zurbuchen,
University of Michigan

We use a path based approach to construct initial guesses and find optimal spacecraft trajectories. The algorithm searches for the control and states that generate a trajectory that is near integrable. The path functions allow ephemeris constraints to be directly substituted into the path ensuring that the trajectory solves the targeting problem. The numerical method used to solve the resulting optimization problem uses a second order Taylor approximation of the cost function and the constraints. Search directions are selected such that they maintain the constraint equations to the second order and cause a decrease in the cost function.

AAS 07 – 157

An Architecture for Incorporating Interactive Visualizations into Scientific Simulations

Ravishankar Mathur and Cesar A. Ocampo, University of Texas at Austin

As scientific simulations get increasingly complex, so must the visualizations used to interpret the data produced. The research undertaken here introduces an architecture by which a simulation programmer can easily add interactive 3D visualizations to their simulations. Common aspects of all simulations are identified, and are used to develop a general ``visualization language" that can be used by any simulation designer to specify what they want to visualize. In addition, a programming interface called OpenFrames is introduced, which allows a simulation developer to use the visualization language from within their own application to easily visualize their results.

AAS 07 – 158

Automatic Determination of Finite Difference Derivative Step Sizes for Indirect Trajectory Optimization

Scott Zimmer, University of Texas at Austin

This paper presents a method to automatically generate the step size for the finite difference derivatives needed to solve indirect trajectory optimization problems. The technique provides a method to estimate the optimal finite difference step size and provides an estimate of the derivative errors. The method removes the burden of tuning step sizes in order to obtain convergence. Because determining the optimal step size for every iteration is computationally intensive, the method allows the user to optimize the step size whenever the error in the derivative exceeds some tolerance.

AAS 07 – 159

Comparison of Fixed and Variable Time Step Trajectory Integration Methods for Cislunar Trajectories

Michael W. Weeks, NASA Johnson Space Center;
Stephen W. Thrasher, C.S. Draper Laboratory

Due to the nonlinear nature of the Earth-Moon-Sun three-body problem and non-spherical gravity, CEV cislunar targeting algorithms will require many propagations in their search for a desired trajectory. For on-board targeting especially, the algorithm must have a simple, fast, and accurate propagator to calculate a trajectory with reasonable computation time, and still be robust enough to remain stable in the various flight regimes that the CEV will experience. This paper compares Cowell's method with a fourth-order Runge-Kutta integrator (RK4), Encke's method with a fourth-order Runge-Kutta-Nyström integrator (RKN4), and a method known as Multi-Conic. Additionally, the study includes the Bond-Gottlieb 14-element method (BG14) and extends the investigation of Encke-Nystrom methods to integrators of higher order and with variable step size.

AAS 07 – 160

Comparison of a Simple Patched Conic Trajectory Code to Commercially Available Software

Brooke M. Anderson Park and Henry Wright, NASA Langley Research Center

Often in spaceflight proposal development, mission designers must evaluate numerous trajectories as different design factors are investigated in the design process. Although there are numerous commercial software packages available to help develop and analyze trajectories, most take a significant amount of time to develop the simulations themselves, which isn't effective when working on proposals. Thus a new code, PatCon, that is both quick and easy to use, was developed to help mission designers run trade studies on launch and arrival times for any given planet.

AAS 07 – 161

Developing a Systematic Approach to the Use of Genetic Algorithms for the Solution of Optimal Spacecraft Trajectory Problems

Bradley J. Wall and Bruce A. Conway, University of Illinois at Urbana-Champaign

A relatively recent method known as the method of Genetic Algorithms (GA's) is perhaps the best known of several "evolutionary algorithms"; that is, algorithms that attempt to evolve toward the optimal solution. GA's have been used to solve a number of spacecraft trajectory optimization problems however, only in an ad hoc way; i.e. no definitive rules (or recommendations) have been established for the solution of various types of problems in orbital mechanics. This work is an initial attempt to categorize tailoring of the GA for various types of problems commonly encountered in spacecraft trajectory optimization.

SESSION 10: ORBIT DETERMINATION AND TRACKING II
Chair: Paul Schumacher, Air Force Research Laboratory

AAS 07 – 162
Expected Orbit Determination Accuracy of High Altitude, Highly Inclined Satellite Orbits

Brandon A. Jones and George H. Born, University of Colorado;
David B. Goldstein, United States Air Force

This study seeks to estimate the expected orbit determination accuracy for high altitude, highly-inclined satellite orbits using pseudo-range and carrier phase GPS measurements. Gipsy-Oasis II was used for both observation simulation and satellite state estimation. Data simulation and error estimation was accomplished through batch processing of various satellite orbits through a prescribed range of initial conditions. Results demonstrate the expected state estimation accuracy given a desired orbit type, eccentricity and altitude.

AAS 07 – 163
Functional Relationship Between Time and True Anomaly for Near-Circular Orbit With Quadratic Drag

Thomas Carter, Eastern Connecticut State University;
Mayer Humi, Worcester Polytechnic Institute

In this paper we seek approximate closed-form solutions for the flight time in terms of the true anomaly for a satellite in a high near-circular orbit that decays as a result of atmospheric drag. Solutions of this problem are attempted based on three models that approximate the atmospheric density. For the first model and in certain special cases of the other two models, solutions are found that compare favorably with numerical simulations.

AAS 07 – 164
Withdrawn

AAS 07 – 165
Macro-Model Tuning Experiment for ICESat Precision Orbit Determination

Hyung-Jin Rim, Charles E. Webb, Sungpil Yoon and Bob E. Schutz,
University of Texas at Austin

A macro model was developed for modeling radiation pressure forces in ICESat Precision Orbit Determination. This model consists of a six-sided box and two flat plates, representing the satellite's body and the solar panels. The optical properties assigned to each of these surfaces were derived from a least-squares fit to the forces from a micro-model developed by Ball Aerospace prior to the launch. This study re-visited the macro model parameters. These parameters were adjusted by using the actual ICESat tracking data.

SESSION 11: SOLAR SAILS
Chair: Felix Hoots, The Aerospace Corporation

AAS 07 – 124

Solar Sail Model Validation from Echo Trajectories

Andrew F. Heaton, NASA Marshall Space Flight Center;
Adam T. Brinckerhoff, University of Michigan

The NASA In-Space Propulsion program has been engaged in a project to increase the technology readiness of solar sails. The effort included software tools to model solar sail guidance, navigation and control. The Echo 1 and Echo 2 balloons were comprised of aluminized Mylar, which is the near-term material of choice for solar sails. Thus Echo 1 and Echo 2 are excellent historic missions for testing the new software tools. We present the results of studies of Echo trajectories that validate solar sail models of optics, solar radiation pressure, shape and low-thrust orbital dynamics.

AAS 07 – 166

Orbital Precession Via Cyclic Pitch for the UltraSail System

Jennifer Hargens-Rysanek, Victoria L. Coverstone and Rodney L. Burton,
University of Illinois at Urbana-Champaign

UltraSail is a non-traditional approach, utilizing innovative solar sail architecture to achieve sail areas approaching 1 km-squared. The payload resides in a central bus. Attached to this bus are several “blades” of solar sail film material that are controllable by a tip satellite at the end of each blade. This paper focuses on the dynamics and control of this UltraSail blade/tip satellite system, specifically the precession of each tip satellite/blade system. Cyclically pitching was shown to be a viable method to precess the spin-axis of the blade/tip satellite system, as well as provide considerable fuel savings over using only thrusters.

AAS 07 – 167

Static Deployment of Large Membrane of Spinning Solar Sail Using a Balloon

Osamu Mori, Maki Shida, and Jun’ichiro Kawaguchi, Japan Aerospace Exploration Agency; Shuhei Nishimaki, Michihiro Matsumoto, Yusuke Shibasaki, and Fuminori Hanaoka, University of Tokyo; Masataka Arakawa, Tokyo Denki University;
Masayuki Sugita, Aoyama Gakuin University

ISAS/JAXA is studying the spinning solar sail mission concept for future applications to deep space explorations. Deployment method for large thin membranes is important. We demonstrated static deployment of the square sail of 20 m diagonal at 37 km altitude using a balloon in August. The size of a membrane is the largest in the world, and to deploy a membrane statically is the first achievement in the world. This paper presents the system and results of the experiment, and discusses the behavior of the membrane. The results of numerical simulation using multi-particle model are compared with the experimental data.

AAS 07 – 168
Withdrawn

SESSION 12: EARTH AND PLANETARY MISSIONS I
Chair: L. Alberto Cangahuala, Jet Propulsion Laboratory

AAS 07 – 169
An Interplanetary Mission to Neptune System: Gravitational Capture and Maneuvers Around Triton

Carlos Renato Huaura Solórzano and Antonio Fernando Bertachini de Almeida Prado, National Institute for Space Research (INPE);
Othon Cabo Winter, Universidade Estadual Paulista (UNESP-FEG)

In a recent study performed by NASA it was proposed, with high priority, a mission to the Neptune's System. Hammel, in 2002, proposed in details the main targets of this mission to Neptune. Recently, Solórzano, in 2006, proposed a mission to Neptune, analysing several schemes for the trip from Earth to Neptune. In this work, our main objective is to show the main characteristics of the gravitational capture of a spacecraft by Triton. As a secondary objective, we can give the fuel consumption for other types of maneuvers to compare with the one performed with the gravitational capture.

AAS 07 – 170
Early Navigation Results for the New Horizons Mission to Pluto/Charon

E. Carranza, A. Taylor, J. Miller, D. Stanbridge, B. Page, J. Smith, P. Wolff, B. Williams, and L. Efron, KinetX, Inc.;
R. Farquhar and Y. Guo, Johns Hopkins University Applied Physics Lab

The New Horizons mission is being flown as the first mission in NASA's New Frontiers Program. The spacecraft was launched January 19, 2006, and with have its first planetary flyby of Jupiter on February 28, 2007. After this, the spacecraft will continue for eight-and-one-half years of interplanetary cruise leading to flyby of the Pluto/Charon system in July 2015. This paper gives a description of the navigation system developed for the New Horizons mission, along with the navigation results obtained thus far from calibrating and testing the navigation system, including attitude and small force modeling and the use of Delta-DOR.

AAS 07 – 171

Earth to Venus-1 Navigation Results for NASA's MESSENGER Mission to Mercury

A. Taylor, E. Carranza, J. Miller, D. Stanbridge, B. Page, J. Smith, P. Wolff, B. Williams and L. Efron, KinetX, Inc.; R. Farquhar, J. McAdams and D. Dunham, Johns Hopkins University Applied Physics Laboratory

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission was launched on 3 August 2004 to begin its six-and-one-half-year interplanetary cruise to arrive in orbit about Mercury beginning in March 2011. The cruise phase includes planetary gravity-assist flybys of Earth (August 2005), Venus (October 2006 and June 2007) and Mercury (January and October 2008, and September 2009). Navigation results from Earth flyby through Venus flyby 1 are presented for orbit determination, maneuver design and reconstruction, and trajectory optimization. Also included are preliminary results from tests of opnav images and Delta-DOR taken on approach to Venus.

AAS 07 – 172

ExoMars Mission Analysis and Design - Entry, Descent and Landing

Rodrigo Haya Ramos and Davide Bonetti, Deimos Space S.L.;
Dave Northey, Dave Gittins and Dave Riley, Analyticon Limited;
Stefano Portigliotti and Maurizio Capuano, Alcatel Alenia Space Italia

ExoMars is ESA's current mission to planet Mars aimed for launch between 2011 and 2013. This paper regards the mission analysis and design of the Entry, Descent and Landing (EDL) phases. It is driven by the flexibility in terms of landing site, arrival dates and the very stringent requirement in terms of landing accuracy. Innovative approaches in terms of worst-case philosophy have been designed. The design of the D&L phases is driven by the mass of the Lander, the limited mass budget for the overall DM, the safe separation of the frontshield and the mass margins philosophy.

AAS 07 – 173

ExoMars Mission Analysis and Design - Launch, Cruise and Arrival Phases

Juan L. Cano and Augusto Caramagno, Deimos Space S.L.;
Valeria Catullo and Carlo Cassi, Alcatel Alenia Space Italia

ExoMars is ESA's current mission to planet Mars. The current mission baseline is based on a Soyuz-Fregat launch from Kourou in 2011 (back-up in 2013) of a spacecraft composite bearing a Carrier and a Descent Module (DM). The trajectory profile is characterized by the need to send the highest possible mass to Mars. This conditions the design in two main ways: launch into a highly elliptic orbit (HEO) and escape in a sequence of apogee rising maneuvers and perform a delayed transfer of type 3 to Mars. This paper regards the interplanetary mission design from launch up to the start of the EDL phase.

AAS 07 – 174

Geostationary LEOP of a SpaceBus4000 from Alcatel With Sea Launch: Flight Dynamics Aspects of the Mission Analysis and Operations

Sylvain Delattre, CNES

A satellite based on a spacebus4000 platform from Alcatel was launched with Sea Launch launcher on August 2006. As it was the first operations for CNES with this launcher, specific Mission Analysis studies were performed including constraints of the mission (interferences, collision, cost, duration, robustness). The LEOP was then realized differently due to an unexpected injection. Flight Dynamics computed a new strategy in real time with operational means to reduce LEOP duration without overcost. The total duration of the mission was reduced of three days, thanks to strategy choices made during transfer phase.

AAS 07 – 175

Low Road to Mars: Venus-Mars-Earth Cycler

Andrew E. Turner, Space Systems/Loral

This paper introduces a Venus-Mars Cycler to facilitate Earth-Mars travel. Advantages of this novel concept over proposed Earth-Mars Cyclers is discussed, including considerations of travel duration, launch opportunity frequency, and the total velocity increment to complete an Earth-Mars round-trip mission. The capability of Venus to modify interplanetary trajectories significantly has already been flight-proven by a number of U.S. and Russian spacecraft, while Mars is of insufficient mass to generate a useful gravity assist. This paper extends this concept for cost-effective travel to and from Mars, the long-term goal of the space programs of the U.S. and other countries.

SESSION 13: ATTITUDE DYNAMICS AND CONTROL

Chair: Don Mackison, University of Colorado

AAS 07 – 177

Saving Mass in Optimally Sizing a Small Satellite Energy Storage and Attitude Control System

David J. Richie and Vaios J. Lappas, Surrey Space Centre, University of Surrey

The recent advent of miniature single gimbal control moment gyroscopes has spawned interest in variable speed versions for energy storage and attitude control systems on small satellites. Although much has been studied on the theory behind such a system, little has been done in optimally sizing these actuators for small satellite applications. Therefore, this paper investigates the fundamental design concepts, optimal sizing, and mission benefits for these actuators. Given a set of small satellite agility and energy storage requirements, an optimal, nonlinear programming method is applied to this problem.

AAS 07 – 178

Spacecraft Attitude Control Using Aerodynamic Torques

M. Luke Gargasz and Nathan A. Titus, Air Force Institute of Technology

This paper studies spacecraft attitude control using aerodynamic torques. Aerodynamic torque is modeled with partial accommodation theory, assuming known accommodation coefficients. A rotating atmosphere with an exponential density is used. The nonlinear equations of motion incorporate drag flaps for attitude actuation. Spacecraft geometry consists of a cubical bus and six drag flaps used in pairs to provide control of roll, pitch, and yaw. Two control laws are compared, one based on nonlinear control theory and one using linear quadratic regulator theory. Simulations demonstrate that both controllers regulate the spacecraft attitude in multiple orbit types over a small range of orientations.

AAS 07 – 179

A Separation Property for the Rigid-Body Attitude Tracking Control Problem

Dongeun Seo and Maruthi R. Akella, University of Texas at Austin

It is a well known fact that quaternion based proportional-derivative controllers for rigid-body attitude motion guarantee global asymptotic stability in both set-point regulation and trajectory tracking objectives. However, the quaternion vector is never directly measured and therefore in practice, controllers employing quaternion feedback should invariably be coupled with appropriate attitude estimators that permit sufficiently fast reconstruction of the quaternion state vector. The primary contribution of this paper is the demonstration of a nonlinear separation property for the attitude control problem that preserves global asymptotic stability results even when the feedback controller uses only instantaneous estimates of the quaternion state.

AAS 07 – 180
Withdrawn

AAS 07 – 181

Combined Singularity Avoidance for Variable Speed Control Moment Gyroscope Clusters

David J. Richie, Vaios J. Lappas and Sajjad Asghar,
Surrey Space Centre, University of Surrey

This work proposes two algorithms extended from existing steering laws which link conventional control moment gyroscope and recent variable-speed control moment gyroscope theory for the more general case of simultaneous attitude plus power tracking using a cluster of actuators. These extended steering laws are then further studied for the case of constrained gimbal angles and saturated wheel speeds in the attitude plus power tracking problem.

AAS 07 – 182

Spacecraft Attitude Control Using Symmetric Stereographic Orientation Parameters

Charles M. Southward II, Joshua R. Ellis, and Hanspeter Schaub,
Virginia Polytechnic Institute and State University

A minimal set of rigid body attitude coordinates, Symmetric Stereographic Orientation Parameters (SSOPs), are investigated for constrained spacecraft pointing problems. These coordinates are found through a general stereographic projection of the Euler parameter unit constraint hypersphere onto a three dimensional hyper-plane. The SSOP coordinates have the unique feature that the associated mathematical singularity can be placed at a desired principal rotation angle by adjusting the projection point. An attitude feedback control law in terms of SSOPs will inherently avoid reaching this singular attitude description, and thus constrain the attitude error response to be within a well defined cone.

SESSION 14: ATMOSPHERIC DENSITY MODELING

Chair: Craig McLaughlin, University of North Dakota

AAS 07 – 183

Atmospheric Modeling Using Accelerometer Data During Mars Reconnaissance Orbiter Aerobraking Operations

R. Tolson, E. Bemis, S. Hough, and K. Zaleski, North Carolina State University;
G. Keating, George Washington University; J. Shidner, S. Brown, A. Brickler,
M. Scher, and P. Thomas, University of Maryland

During MRO aerobraking, accelerometer data were used to determine the density, density scale height, orbit-to-orbit variability, latitudinal-seasonal variations, longitudinal waves and other phenomena in the thermosphere. The RMS noise was about 0.004 mm/s^2, which, ignoring other errors would permit density recovery to about 0.008 kg/km^3, more than an order of magnitude improvement from previous missions. Details are given of aerobraking operations, the accelerometer data analysis methods and operational procedures. Applications to determining thermospheric properties, interesting atmospheric phenomena encountered during MRO and correlation with the MGS and Odyssey missions is presented. Some remaining issues on interpretation of the data are also provided.

AAS 07 – 184

Withdrawn

AAS 07 – 185

Improving Dynamic Calibration of the Atmosphere

Matthew P. Wilkins, Schafer Corporation;
Chris Sabol, Air Force Maui Optical and Supercomputing Site;
Paul J. Cefola, Consultant; Kyle T. Alfriend, Texas A&M University

Dynamic calibration of the atmosphere is a technique where corrections to atmospheric density models are generated based upon indirect observations of the atmosphere, typically satellite orbital data. In this work, the density correction theory proposed by Nazarenko and Yurasov is revisited and modifications to the theory are examined. Based upon observations during the validation of the Russian DCA theory, we saw that successive refinements to the density corrections provided a small yet appreciable improvement to the smoothing of the ballistic factor. Additionally, we explored other parameterizations in an attempt to remove additional uncertainty in the ballistic factor estimation process.

AAS 07 – 186
Withdrawn

AAS 07 – 187
Withdrawn

AAS 07 – 188

Thermospheric Density Model Including Magnetospheric Energy Sources at Quiet Times

Kenneth Moe and Mildred M. Moe, Space Environment Technologies

At geomagnetically quiet times, there is a large energy source at high latitudes. It produces a prominent dayside density bulge which is dependent on universal time and is coupled to the location of ionospheric electron density peaks, the red airglow, and particles precipitating from the magnetosphere. We present an analytical semi-empirical model which reproduces the neutral density bulges at high latitudes in the northern and southern hemispheres.

AAS 07 – 189

Validation and Application of Corrections to the NRLMSISE-00 Atmospheric Density Model

Matthew P. Wilkins, Schafer Corporation;
Chris Sabol, Air Force Maui Optical and Supercomputing Site;
Paul J. Cefola, Consultant; Kyle T. Alfriend, Texas A&M University

Dynamic calibration of the atmosphere is a technique where corrections to atmospheric density models are generated based upon indirect observations of the atmosphere, typically satellite orbital data. In this work, the density correction theory proposed by Nazarenko and Yurasov is independently vetted and validated. The corrections are generated for the NRLMSISE-00 atmospheric density model from November 31, 1999 through December 1, 2003 and are compared to published results of Nazarenko and Yurasov. A second set of corrections was generated over the four years prior during a relatively quiet space weather period. Comparing the corrections generated during these two periods allows us to draw conclusions regarding our ability to compute density model corrections.

SESSION 15: TETHERED SATELLITES
Chair: Thomas Eller, Astro USA, LLC

AAS 07 – 190

A Permanent Tethered Observatory at Jupiter: Dynamical Analysis

J. Peláez, Technical University of Madrid (UPM);
D. J. Scheeres, University of Michigan

Outer planet exploration has always been handicapped by a scarcity of power. The traditional way, solar energy converted to electricity, becomes rapidly ineffective as one travels further from the Sun. Electrodynamic tethers could be used as an interesting alternative to produce onboard energy. This paper describes the essential dynamical issues arising in the placement of a permanent Jupiter observatory located at one of its inner moonlets and sustained by an electrodynamic tether working in the generator regime. The aim of the work is to analyze the main aspects related with the orbital dynamics and attitude dynamics of this system.

AAS 07 – 191

Dynamics of an Electrodynamic Tether System Containing Gyrostat End Bodies

Joshua R. Ellis and Christopher D. Hall,
Virginia Polytechnic Institute and State University

We study the dynamics of an electrodynamic tether system consisting of two gyrostats and a flexible tether. Each gyrostat contains an arbitrary number of wheels and thrusters, and the tether is modeled as a linearly elastic string that resists stretching, but not bending or twisting. The tether is spatially discretized using the assumed mode method. The system equations of motion are numerically integrated for several scenarios, and the results of these simulations are used to analyze the relationship between the dynamics of the tether under the influence of an electrodynamic force and the attitude dynamics of the end bodies.

AAS 07 – 192

Evolutionary Computation of Tether Deployment Trajectories With Application to YES2

Paul Williams, RMIT University, Australia;
Marco Stelzer, Andrew Hyslop and Michiel Kruijff, Delta-Utec, The Netherlands

This paper considers the design of trajectories for the deployment of the YES2 tether. Various methods for optimizing the deployment strategy are considered. First, a reduced system model that represents the tether as a straight inelastic rod is used to develop deployment trajectories using direct transcription techniques. A validation model that treats the full tether elasticity and flexibility is used to perform Monte Carlo simulations of the deployment under parametric uncertainties. The critical case occurs if the deployer has larger than expected friction and the ejection velocity is lower than anticipated. It is necessary to re-optimize using evolutionary techniques.

AAS 07 – 193

Hybrid Control of Orbit Normal and Along-Track 2-Craft Coulomb Tethers

Arun Natarajan and Hanspeter Schaub,
Virginia Polytechnic Institute and State University

The dynamics and stability of a charged two craft satellite formation with nominal fixed separation distance (Coulomb tethers) is studied when the cluster is aligned with the along-track and orbit normal direction. Unlike the charged 2-craft formation scenario aligned along the orbit radial direction, the feedback control law using inter-spacecraft electrostatic coulomb forces and the differential gravitational accelerations is not sufficient to stabilize the Coulomb tether length or its attitude. Therefore, a hybrid feedback control law combining conventional thrusters and coulomb forces is presented. This hybrid feedback control is designed to asymptotically stabilize the satellite while avoiding plume impingement issues.

AAS 07 – 194

Libration Control of Electrodynamic Tethers Using the Extended Time-Delayed Autosynchronization Method

M. Iñarrea, La Rioja University; J. Peláez, Technical University of Madrid (UPM)

To overcome the difficulties associated with dynamic instabilities of electrodynamic tethers, a new control scheme has been analyzed in this paper. We add appropriate forces to the system with the aim of converting an unstable periodic orbit of the governing equations into an asymptotically stable one. We use an extended time-delay feedback control scheme which has been used successfully in problems with one degree of freedom. In order to obtain results with broad validity, some simplifying assumptions have been introduced in the analysis. Thus, we assume a rigid tether with two end masses orbiting along a circular, inclined orbit.

AAS 07 – 195

Withdrawn

AAS 07 – 196

Power Generation Using Self-Balanced Electrodynamic Tethers in Debris Mitigation Scenarios

M. Sanjurjo and J. Peláez, Technical University of Madrid (UPM)

In debris mitigation scenarios, the most effective tether regime is the deorbiting mode since it provides the minimum deorbiting time; in this regime the electrodynamic tether uses no load. Nevertheless, there exist missions with other requirements like slower descents enlarging the operational life of spacecraft or reusable vehicles. In these cases, a mixture of power generation and orbit transfer is needed. This paper explores the possibility of profit from the decay process of space debris. We focus on the power generation, establishing the dissipation sources of mechanical energy and studying different configurations. Numerical simulations support the theoretical results.

SESSION 16: SATELLITE CONSTELLATIONS & FORMATION FLYING III
Chair: Thomas Alan Lovell, Air Force Research Laboratory

AAS 07 – 110

Modified Equations of Motion Around Circular Trajectory and its Application to Formation Flying Control

Jun'ichiro Kawaguchi,
Institute of Space and Astronautical Science (ISAS), Japan Aerospace Agency

Usually, the formation flying associated with a circular orbit is discussed through the well-known Hill's equations of motion. This paper presents and discusses the formation-fixed coordinate to discuss the formation behavior. The resulting equations take the non-autonomous form and depict some interesting characteristics. The paper also presents the application of decentralized formation control strategy that stabilizes and enables a quick reaction to the command.

AAS 07 – 197

Fuzzy Logic Control System for Reconfiguration Procedure Applied to the NASA Benchmark Tetrahedron Constellation

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

In formation flying, the reconfiguration procedures are difficult and involve a lot of mathematical computation to resolve the problem in an optimal way. The reconfiguration procedure of the proposed NASA benchmark tetrahedron constellation is more complicated because of the required locations of the four spacecraft at the apogee point. In this paper, for the first time, a fuzzy logic controller is used to reconfigure the constellation with the Lagrange Planetary Equations. The Lagrange Planetary Equations are a set of a non-linear equations consisting of propulsive requirements to vary the orbital elements. The fuzzy logic controller will be used to obtain the desired orbital dimensions for a single satellite, but this controller can be applied to the configuration of the constellation.

AAS 07 – 198

GPS Hardware-in-the-Loop Spacecraft Formation Flying Simulation

Scott A. Kowalchuk and Christopher D. Hall,
Virginia Polytechnic Institute and State University

The result of a Global Positioning System (GPS) hardware-in-the-loop simulation of two spacecraft flying in formation is presented. The simulations involve a chief spacecraft in a low Earth orbit (LEO), while a deputy spacecraft maintains an orbit position relative to the chief spacecraft. An orbit correction maneuver (OCM) for the deputy spacecraft is accomplished using a classical orbital element (COE) controller. The position of the deputy is determined from a GPS receiver that is connected to a GPS hardware-in-the-loop simulator. From the current relative positions of the spacecraft the COE controller determines the OCM for the deputy spacecraft.

AAS 07 – 199

Optimal Design of Satellite Formation Relative Motion Orbits Using Least Squares Methods

Hui Yan, Kyle T. Alfriend, Srinivas R. Vadali and Sengupta Prasenjit,
Texas A&M University

Formation flying design can be considered as searching for six initial conditions in the local vertical local horizontal frame or differential orbital elements. In this paper, a novel approach is proposed to design formation flying with a least squares technique. We take the desired formation geometry as the reference values, and then the initial conditions of relative motion can be analytically solved by a linear least squares approach. Also we show using Gaussian least squares differential correction to design nonlinear formation flying. Numerical results demonstrate that the approach works well.

AAS 07 – 200

Study of Lunar Constellations for Situational Awareness and Surveillance

Devon S. Sanders and Carrie D. Olsen, Mississippi State University

A method for design of lunar constellations for ground observation is presented. Such constellations could be used to improve situational awareness for astronauts and ground controllers conducting extensive lunar surface operations. The design method considers single orbit parameter trade studies, the use of specialty orbits, such as sun-synchronous and frozen orbits, and analyzes candidate constellation configurations based on ground coverage metrics and station-keeping costs. The paper concludes with a set of recommendations for lunar constellation design, generalizing the method to apply to a broader class of lunar orbiting satellite constellations.

AAS 07 – 202

Optimal Configuration of a Planet-Finding Mission Consisting of a Telescope and a Constellation of Occulters

Egemen Kolemen and N. Jeremy Kasdin, Princeton University

The optimal configuration of satellite formations consisting of a telescope and multiple occulters is studied. The objective is to enable the imaging of the largest possible number of satellites with minimum mass requirement which consists of the dry mass of the spacecraft and the total fuel requirement for the formation. Fuel-free, maximum sky coverage quasi-periodic orbits are identified employing a multiple Poincare section method. Subsequently, the subproblems of constellation initialization, and the sequencing and timing of the imagining sessions are optimized for minimum fuel. A trade-off study of various constellations is performed.

AAS 07 – 203

Optimal Control of a Circular Spacecraft Formation Subject to Gravitational Perturbation

Jason L. Baldwin and Nathan A. Titus, Air Force Institute of Technology

This paper develops the optimal open-loop control to maintain a circular relative spacecraft formation. The nonlinear equations of motion include two-body and J2 gravitational terms. The primary orbit is assumed to be circular and inclined. The optimal trajectory is found using a traditional calculus of variations-based approach, requiring the numerical solution of a two-point boundary value problem. Convergence is dependent upon the choice of boundary conditions, but using the initial states for a circular formation derived analytically from linearized equations provides reasonable results. For an 800-km orbit, delta-v costs are approximately 40 m/s/year, with exact values dependent upon error tolerances.

AAS 07 – 204

Withdrawn

SESSION 17: TRAJECTORY DESIGN AND OPTIMIZATION III

Chair: Dennis Byrnes, Jet Propulsion Laboratory

AAS 07 – 205
Withdrawn

AAS 07 – 206

Fine Positioning Techniques in Geostationary Transfers: Benefits of a Linear Approach

Sebastien Fourest, CNES

Fine positioning of geostationary satellites is an issue difficult to optimize properly. Numerical software appear not to be the most suitable ones, as the problem presents many local optima and is highly dependant on the initial solution. On the other hand, analytical algorithms make it possible to perform high speed computation (Monte Carlo analysis, instantaneous graphical visualization), leading to a new approach of the problem, much more comprehensive and reliable. A set of tools based on linear analysis (simplex, genetic algorithms,…) was developed in order to increase the performances of the geostationary transfers at CNES facilities (saving fuel and time).

AAS 07 – 207

Indirect Optimization of Three-Dimensional Finite-Burning Interplanetary Transfers Including Spiral Dynamics

Christopher L. Ranieri and Cesar Ocampo, University of Texas at Austin

The minimum fuel indirect optimization problem for a three-dimensional Low Earth Orbit to Low Mars Orbit transfer is solved using a step-by-step process developed previously for the two- dimensional model and techniques to estimate the co-states for three-dimensional spirals. Using a newly derived transformation, the entire trajectory, including the Martian capture, is integrated in an Earth-referenced frame. As in the two-dimensional case, more fuel efficient trajectories are found compared with the same trajectories published in other studies. Whereas previous research only achieved final Martian orbits of 20382 km, the new approach achieves lower orbits of 5000-6794 km.

AAS 07 – 208

Exploration of Interval Picard Methods for Trajectory Family Propagation

Benjamin F. Villac, University of California at Irvine;
Alan H. Barr, California Institute of Technology;

An interval Picard integration method is investigated for applications to spacecraft propagation problems in a self-validated computational framework. The method provides state information at all times along a computed trajectory segment with guaranteed error bounds. Finite precision computations and inaccurate model parameters information are automatically taken into account, and extended sets of initial conditions can also be computed at once, without the need to resort to Monte Carlo simulations. This method opens the possibility for a deterministic approach to trajectory guidance and navigation in a fully nonlinear framework. The computational complexity, limitations and some alternative approaches are discussed.

AAS 07 – 209

Multiple Leg Fuel-Optimal Trajectories for Hovering Satellites

David J. Irvin, Jr. and Richard G. Cobb, Air Force Institute of Technology

The majority of recent work in relative satellite dynamics has concentrated on closed or drifting orbits of a deputy about a chief satellite, assumed to be located at the center of a local reference frame. A problem of interest to mission planners is the ability to hover in a prescribed vicinity of a chief satellite for an extended period of time. Recent research has identified fuel-optimal paths in the relative frame for single leg trajectories in the orbit plane of the chief. This research extends that work to find multiple leg, fuel-optimal trajectories for true hover capability.

AAS 07 – 210

Optimal Rendezvous and Docking Simulator for Elliptical Orbits

Haijun Shen and Christopher D. Karlgaard, Analytical Mechanics Associates, Inc.

This paper describes the development and implementation of a simulation environment for spacecraft rendezvous and docking guidance, navigation, and control in elliptical orbits. The rendezvous and docking simulator, known as DOCKSIM, functions in two phases. In the first phase, optimal trajectories are obtained for the point mass model of the docking vehicle subject to path constraints, with the target vehicle in a known elliptical orbit. In the second phase, the chaser vehicle is considered as a rigid body whose attitude and trajectory is controlled such that its docking port is aligned with the target vehicle at the time of docking, and the flight path closely follows the optimal trajectory.

AAS 07 – 211

Survey of Global Optimization Methods for Low Thrust Multiple Asteroid Tour Missions

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

With the recent successful launches of Deep Space 1, SMART-1, and Hayabusa, electric propulsion has become a viable option for robotic missions, enabling shorter flight times, fewer required planetary gravity assists, smaller launch vehicles, and/or larger payloads. Global optimization of a low-thrust trajectory with multiple targets and gravity assists, however, is a difficult problem, due to the multi-modality and large size of the design space. This paper surveys various low-thrust trajectory optimization techniques combined with global optimization methods to assess their efficacy and applicability to a low-thrust, multiple asteroid tour mission.

SESSION 18: ATTITUDE DETERMINATION AND CONTROL
Chair: Yunjun Xu, University of Oklahoma

AAS 07 – 212
Attitude Acquisition of a Satellite with Partially Filled Liquid Tank

Ja-young Kang, Hankuk Aviation University

Three-axis stabilized communications satellites launched into GEO on conventional launchers must make a transition in attitude control from the spinning state of the initial mission phases to long-term earth pointing stabilized state. One method of achieving the transition utilizes the momentum transfer maneuver, in which the spacecraft momentum is transferred from initially normal to the system's momentum vector. This method has been studied for a long time and implemented widely. In this paper, the similar technique is applied for reorientation of a satellite containing partially filled spherical tank and the effect of slosh motion on attitude acquisition is investigated qualitatively.

AAS 07 – 213
Averaging Quaternions

F. Landis Markley, NASA Goddard Space Flight Center;
Yang Cheng and John L. Crassidis, University at Buffalo;
Yaakov Oshman, Technion - Israel Institute of Technology;

Attitude estimation often requires finding the average of a set of attitude estimates in quaternion form with associated weights. The simple weighted average has two flaws that are discussed in the paper. The observation that we really want to average attitudes rather than quaternions provides a way to avoid these flaws. The average quaternion should minimize a weighted sum of the squared Frobenius norms of attitude matrix differences. The paper contains simulation results of the averaging algorithm as well as results from specific applications, such as using the algorithm for attitude estimation with particle filters.

AAS 07 – 214
Withdrawn

AAS 07 – 215
Issues in Robustification of Iterative Learning Control Using a Zero-Phase Filter Cutoff

Richard W. Longman and Wondo Kang, Columbia University

Iterative learning control (ILC) aims to converge to zero tracking error in control systems that repeatedly perform a maneuver. ILC has the potential to eliminate the detrimental effects of flexibility on pointing accuracy of sensors during repeated scanning maneuvers in spacecraft. A zero-phase low-pass filter is necessary to robustify learning against residual modes. It is shown that the filter can interact with zeros introduced by discretization, aggravating error growth between sample times. A method of predicting the performance of ILC with a cutoff is developed, and used to show how one must pick the cutoff to produce good results.

AAS 07 – 216

Placing the Repetitive Controller Inside or Outside the Feedback Loop: Simultaneously Achieving the Feedback and Repetitive Control Objectives

Richard W. Longman and Joe W. Yeol, Columbia University;
Yeong S. Ryu, State University of New York at Farmingdale

Spacecraft often have internal moving parts such as control moment gyros. Slight imbalance in such equipment sets up vibrations in the spacecraft that can compromise the performance of any fine pointing equipment on board. Repetitive control (RC) is a relatively new field that creates control systems that can in theory totally eliminate the effects of a periodic disturbance source. In many applications, one wants not only to meet this objective, but also to significantly attenuate more general disturbances over a range of frequencies up to a chosen bandwidth. This paper is devoted to presenting methods that can accomplish both objectives.

AAS 07 – 217

Designing Optimized FIR Repetitive Controllers from Noisy Frequency Response Data

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

In spacecraft, small imbalances in reaction wheels produce vibrations that disturb fine pointing equipment. Repetitive control (RC) theoretically can totally eliminate the effects of such disturbances. In two previous works, a very effective method of designing the RC compensator needed for stability based on a given model was developed, and a zero-phase filter design was developed to robustify against residual modes. One can design directly from frequency response information without using a model. This work addresses how one must adjust these effective RC design methods in order to address the influence of noise in the frequency response data.

AAS 07 – 218

On the Periodic Images of Start-Up in Repetitive Control

Richard W. Longman and Jiangcheng Bao, Columbia University

Repetitive control (RC) cancels the effects of a periodic disturbance to a control system, e.g. in an active isolation mount for high precision pointing equipment to eliminate vibrations from a momentum wheel. RC adjusts the feedback control command based on the error one period back. At start up, the command normally has a jump discontinuity, which propagates forward each period. The nature of the propagation and its decay is investigated, both for simple RC laws and for several important classes of more sophisticated RC laws. Methods are developed to prevent or reduce the appearance of such discontinuities.

AAS 07 – 219
Withdrawn

SESSION 19: ORBIT DYNAMICS & PERTURBATIONS II
Chair: Thomas Starchville, The Aerospace Corporation

AAS 07 – 220
A Perturbation Theory for Hamilton's Principal Function: Applications to the Two-Point Boundary Value Problem

Oier Peñagaricano Muñoa and Daniel J. Scheeres, University of Michigan

A perturbation theory for solving two-point boundary value problems is presented. Based on Hamilton's principle and the calculus of variations, this theory allows us to analytically solve for the velocities in the targeting problem. Applications of the theory are found in the fields of orbital mechanics and optimal control. Examples showing the accuracy of the theory in the perturbed two-body problem are presented.

AAS 07 – 221
Analytical Theory for Science Orbits Around Planetary Satellites

Martín Lara, Real Observatorio de la Armada

We provide an analytical theory for spacecraft motion close to synchronously orbiting and rotating planetary satellites. The main perturbations of the motion arise from the non-sphericity of the central body and the planetary perturbation. The ratio rotation rate of the satellite mean motion of the orbiter is the small parameter of our theory. The evolution of the secular terms is obtained up to the fourth order in the small parameter, and the short and long period terms are recovered up to third order through explicit transformations. An application for the computation of long lifetime science orbits is presented

AAS 07 – 222
Withdrawn

AAS 07 – 223
Efficient Gravity Field Computation for Trajectory Propagation Near Small Bodies

Andrew Colombi and Anil N. Hirani, University of Illinois at Urbana-Champaign; Benjamin F. Villac, University of California at Irvine

A finite element approach for gravity potential computation near arbitrary shaped small bodies, and an interpolation scheme for fast retrieval of the force field are presented. This set of tools is shown to significantly reduce the computational effort for trajectory integrations around small bodies when compared to the current approaches (series expansions and polyhedron method). This method is expected to provide a better foundation for Monte Carlo analysis of spacecraft guidance and navigation in proximity operation of small bodies and help in the design of future asteroid or comet missions.

AAS 07 – 224

Energy Constraints in the Restricted Full Three-Body Problem: Application to Binary System 1999 KW4

Julie Bellerose and Daniel J. Scheeres, University of Michigan

We give a general description of the dynamics of a particle in the gravitational field of a binary system. In this model, we consider one of the binary as having a mass distribution and the other as being a sphere. The analogue Lagrangian points and their stability have been studied and analyzed, especially L4,5. For this system, we compute the zero velocity curves, we investigate regions of allowable motion taking into account the ellipsoid body geometry and we investigate the effects of different perturbations. We apply the methods to the binary system KW4 and give some results.

AAS 07 – 225
Withdrawn

AAS 07 – 226

Huygens Titan Probe Trajectory Reconstruction Using Traditional Methods and the Program to Optimize Simulated Trajectories II

Scott A. Striepe, NASA Langley Research Center;
Robert C. Blanchard and Michael F. Kirsch, National Institute of Aerospace;
Wallace T. Fowler, University of Texas at Austin

On January 14, 2005, the ESA's Huygens probe separated from NASA's Cassini spacecraft, entered the Titan atmosphere and landed on its surface. As part of the agreement with ESA, NASA provided results of all analyses and presented findings to the Huygens project team. In return, NASA was provided the flight data from the probe so that trajectory reconstruction could be done and simulation models assessed. Trajectory reconstruction of the Huygens entry probe at Titan was accomplished using two independent approaches: a traditional method and a POST2-based method. Results from both approaches are discussed in this paper.

AAS 07 – 227

Multiple Gravity Assists in the Restricted Three-Body Problem

Shane D. Ross, Virginia Polytechnic Institute and State University;
Daniel J. Scheeres, University of Michigan

We investigate multiple gravity assists which can occur outside of a perturbing body's sphere of influence and which are dynamically connected to orbits that (i) get captured by the perturber or (ii) come from or escape to infinity. We proceed by deriving a symplectic twist map to approximate particle motion. Essential features of the dynamics in the full equations of motion are preserved: the phase space contains a connected chaotic zone where lanes of fast migration between orbits of different semi-major axes can be identified. Numerical examples are given for a spacecraft in the field of Jupiter and Callisto.

SESSION 20: LIBRATION POINT TRAJECTORIES
Chair: Michael Gabor, Northrop Grumman Corporation

AAS 07 – 228
Analysis of Capture Trajectories to Libration Points

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

Spacecraft capture trajectories to the vicinity of the L1 and L2 points in the restricted Hill three-body problem are analyzed. The specific focus is on transfer into these vicinities from interplanetary trajectories. This application is motivated by future proposals to place "Deep Space" ports at the Earth and Mars L1 or L2 points. We consider the feasibility of using aero-assist capture to reduce the cost of transfer into these locations.

AAS 07 – 229
Direct Lunar Halo Orbit Transfers

Jeffrey S. Parker and George H. Born, University of Colorado

This paper provides a robust survey of short-duration, direct transfers from the Earth to lunar Halo orbits. The results show that several families of such transfers exist, including quick four- or five-day transfers, as well as more efficient transfers that require three or more weeks. It has been found that the quick transfers require between 3.6 and 4.1 km/s, depending on the Halo orbit. If more time is available, then any lunar Halo orbit may be reached for at most 3.65 km/s. Finally, this paper addresses the costs and benefits associated with using short-duration, direct transfers to lunar Halo orbits.

AAS 07 – 230
Withdrawn

AAS 07 – 231
Withdrawn

AAS 07 – 232
Periodic Orbits High Above the Ecliptic Plane in the Solar Sail 3-Body Problem

Thomas J. Waters and Colin R. McInnes, University of Strathclyde

Due to the non-central nature of the force on a solar sail, there exist equilibrium points of the equations of motion out of the ecliptic plane in the Sun-Earth-Sail circular restricted 3-body problem, in contrast with the classical Lagrange points. Analogous to the 'halo' orbits, we construct large amplitude periodic orbits about these equilibria. By timing the period of the orbit we may negate the seasonal effects of the variation in the Earth's axis of rotation, and thus the sail's position when viewed from the pole subtends a much smaller angle (around 8 deg rather than 46 deg). These orbits are of practical interest with regards to communication with, and constant imaging of, the poles.

AAS 07 – 233
Withdrawn

AAS 07 – 234

Earth-Sun Triangular Lagrange Point Orbit Insertion and Satellite Station Keeping

Julio Cesar Benavides and David B. Spencer, Pennsylvania State University

We analyze the velocity changes to transfer satellites from Earth orbit to the Sun-Earth triangular Lagrange points and estimate the station-keeping costs and times required for these actions. Analytical, co-orbital rendezvous equations for a circular and elliptical Earth orbit were derived. Velocity changes and times-of-flight for orbital insertion into the triangular points were calculated for various starting locations in Earth's heliocentric orbit. These results were compared to the outcomes of Lambert's problem for various times-of-flight, and the results agreed closely. The smallest velocity changes to reach the triangular points occurred when the transfer started close to Earth perihelion. Station-keeping velocity changes and times-of-flight were inversely proportional to the times-of-flight needed for the correction. Applications using satellites positioned at these points are discussed.

SESSION 21: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL II
Chair: J. Russell Carpenter, NASA Goddard Space Flight Center

AAS 07 – 176

A Fuel-Free Sun-Tracking Attitude Control Strategy and the Flight Results in Hayabusa (MUSES-C)

Jun'ichiro Kawaguchi and Ken'ichi Shirakawa,
Institute of Space and Astronautical Science (ISAS), Japan Aerospace Agency

The paper presents the attitude reorientation taking the advantage of solar radiation pressure without use of any fuel aboard. The strategy is currently adopted to make Hayabusa spacecraft keep pointed toward the Sun for several months. The flight results are presented with the estimated solar array panel diffusion coefficient.

AAS 07 – 235

Single-Frequency GPS Relative Navigation in a High Ionosphere Orbital Environment

Patrick R. Conrad, Cornell University;
Bo J. Naasz, NASA Goddard Space Flight Center

The Global Positioning System provides a convenient source for space vehicle relative navigation measurements, especially for low Earth orbit formation flying and autonomous rendezvous mission concepts. For single-frequency GPS receivers, ionospheric path delay can be a significant error source if not properly mitigated. In particular, ionospheric effects are known to cause significant radial position error bias, and add dramatically to relative position estimation error if the onboard navigation software does not force the use of measurements from common or shared GPS space vehicles. This paper presents results from simulated and hardware-in-the-loop GPS navigation simulations for a pair of space vehicles flying in close proximity and using GPS pseudorange measurements to perform absolute and relative orbit determination.

AAS 07 – 236
Withdrawn

AAS 07 – 237

Martian Aerocapture Guidance Using Artificial Neural Network Trained by Genetic Algorithm

Philippe Cayouette, Jean-François Hamel, and Charles-Antoine Brunet,
Université de Sherbrooke

Aerocapture is a technique that allows a significant reduction of fuel consumption (thus reducing the spacecraft mass) for planetary insertion by dissipating the orbital energy of the vehicle, using the aerodynamic drag created by the passage in the atmosphere of a planet. This article proposes a change of paradigm concerning the aerocapture guidance algorithm: the use of a hybrid Artificial Intelligence technique. In order to be used as a guidance algorithm, a neural network has to be trained with a novel technique, i.e. a genetic algorithm within a navigation-guidance-control simulation loop.

AAS 07 – 238
Withdrawn

AAS 07 – 239
Withdrawn

AAS 07 – 240

Modeling of Dynamics and Control for Gravity Probe B

Ivanka Pelivan and Stephan Theil, University of Bremen;
Sara Smoot and Yoshimi Ohshima, Stanford University

Many scientific space missions have demanding requirements on disturbance rejection. Application of drag-free control techniques eliminates or diminishes the accelerations on a satellite to a level which allows the execution of highly sensitive experiments. A high-fidelity spacecraft dynamics and control simulator has been developed to aid in design, test and verification for missions with a very high level of performance. The simulator is first adapted to Gravity Probe B for dual purpose: Verification of simulator modules is achieved by comparison to flight data but also the science data processing benefits from system identification of previously unmodeled disturbances.

AAS 07 – 241

Modified μ-Synthesis for Drag-Free Control Design

Lorenzo Pettazzi and Stephan Theil, University of Bremen

Drag-free satellite control has been recently used for a number of scientific missions where a test mass is required to follow with high accuracy a pure gravitational trajectory. For a drag-free satellite not all the parameters are known and modeled in the same way. Some of them are usually more difficult or expensive to be estimated. The main objective of the present work is to design a controller that tolerates the maximum possible level of uncertainty in some given parameters while keeping the uncertainty in the other parameters within a certain specified range and achieving the desired level of performance.

SESSION 22: EARTH AND PLANETARY MISSIONS II

Chair: John Seago, Analytical Graphics, Inc.

AAS 07 – 242

A Semi-Analytic Method to Predict Orbit Maintenance Thrust Maneuvers

Christina Doolittle and Frank R. Chavez, Air Force Research Laboratory/VSES

To support the goal of reducing cost and complexity of satellite ground operations, several organizations are considering automating many of the ground operation tasks. The focus of the effort reported herein is on automating the task of predicting when to apply orbit maintenance burns for satellite requiring constant altitude or revisit periods. A semi-analytic method has been developed which will provide a mission planer burn times and durations given a desired orbit altitude or revisit period. Subsequently, the mission planner can work to incorporate these maneuvers into a schedule of tasks for uploading to the satellite for execution.

AAS 07 – 243

Mars Reconnaissance Orbiter Aerobraking Control

C. Allen Halsell, Stuart W. Demcak, Tung-Han You, Ramachand S. Bhat, Eric J. Graat, Earl S. Higa, Dolan E. Highsmith, Stacia M. Long, and Neil A. Mottinger, Jet Propulsion Laboratory; Moriba K. Jah, Oceanit Laboratories Inc.

The Mars Reconnaissance Orbiter spacecraft reached Mars on March 10, 2006 and successfully captured into Mars orbit. The Mars capture orbit was elliptical, with a periapsis altitude of 400 km and an orbit period near 35 hours. The final Primary Science Orbit (PSO) for the orbiter is closer to Mars than any other spacecraft currently operating at Mars (255 km by 320 km). Aerobraking techniques were used to establish this orbit with 445 orbits over a 6-month period, saving over 1200 m/sec. This paper describes the strategy and implementation of the MRO aerobraking phase.

AAS 07 – 244

Mars Reconnaissance Orbiter Operational Aerobraking Phase Assessment

Jill L. Prince and Scott A. Striepe, NASA Langley Research Center

The Mars Reconnaissance Orbiter was inserted into orbit around Mars on March 10, 2005. After Mars Orbit Insertion, the aerobraking phase lasted approximately 5 months during which teams from the Jet Propulsion Laboratory, Lockheed Martin, and NASA Langley Research Center worked together to monitor and maneuver the spacecraft such that thermal margin on the solar arrays was maintained while schedule margin was upheld to provide a final local mean solar time at ascending node of 3:00 PM on the final aerobraking orbit. This paper will focus on the contribution of the flight mechanics team at NASA Langley Research Center.

AAS 07 – 245

Mars Reconnaissance Orbiter Orbit Determination During Aerobraking

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

The Mars Reconnaissance Orbiter spacecraft reached Mars on 10 March 2006 and was put into orbit with an orbital period of 35 hours. Aerobraking through the Mars atmosphere was used to help get the spacecraft into the final low, near circular Primary Science Orbit. This paper describes the orbit determination performed during the MRO aerobraking phase for generating reconstructed and predicted trajectories. Predicted trajectories had several constraints on their accuracies. In order to meet the constraints, the atmospheric density was estimated for each aerobraking orbit. The estimated densities were analyzed and used to generate improved short-term predict models.

AAS 07 – 246

Mission Analysis of the Sample Return from Primitive Type Near Earth Asteroid

Yasuhiro Kawakatsu, Masanao Abe, and Jun'ichiro Kawaguchi, JAXA/ISAS

Reported in this paper is the mission analysis of the asteroid sample return mission. Following the successful achievements of HAYABUSA, the Japanese asteroid explorer, JAXA/ISAS has started the study of the next asteroid exploration mission supposing a launch in the first half of the 2010s. The objective of the next mission is to return the sample from the asteroid with primitive composition. The paper includes the results of the selection of target asteroid, the design of nominal mission sequence, and some back up plans.

AAS 07 – 247

Mission Design Overview for the Phoenix Mars Scout Mission

Mark D. Garcia and Kenneth K. Fujii, Jet Propulsion Laboratory

The Phoenix Mars Scout Lander, scheduled to launch in August 2007, will land on the northern plains of Mars in May 2008, prior to the start of the northern, Martian summer. For three months after landing, the fixed Lander will perform in-situ and remote sensing investigations that will characterize the chemistry of the materials at the local surface, sub-surface, and atmosphere, and will identify potential provenance of key indicator elements of significance to the biological potential of Mars, including potential organics and any accessible water ice. An overview of the mission design from launch through surface operations is described.

AAS 07 – 248

A Determination of Rhea's Gravity Field from Cassini Navigation Analysis

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

The Cassini spacecraft was tracked by the DSN in Canberra and Madrid through its 502-km altitude flyby of Saturn's moon Rhea on 26 November 2005. This has enabled the determination of low harmonics of the Rhea gravity field as part of the routine Cassini orbit determination. Several different orbit determination arcs and filter approaches were used to examine solution sensitivities to data weighting, arc length and the effects of colored solar plasma noise. In addition, the solution sensitivity to the application of a hydrostatic constraint equation $3J_2 = 10C_{22}$, as an inexact constraint, is examined.

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