Monday, February 9, 2009 Sapelo

Session 1: Orbit Determination 1

Chair: Bob Glover
AT&T

08:00 **AAS 09 - 101** **An Extended Methods of Optical Measurements for Identification and Cataloguing of Faint Space Debris Objects**
Pavel Papushev, Institute of the Solar Terrestrial Physics SB RAS, Irkutsk

This paper addresses a strategy and methods using optical measurements for the identification and cataloguing of faint space debris objects. The following results are presented and discussed: a) The description of the equipment, methods and spectrophotopolarimetrical techniques of faint space debris object measurements, b) The statistical data on the color indexes, spectrophotometrical characteristics of the faint space debris objects, and c) Statistical estimates of an opportunity of application of these characteristics for identification and cataloguing of faint space debris objects.

08:25 **AAS 09 - 102** **Utilization of Space Based Cameras to Observe Resident Space Objects**
Scott Bourgeois, Drew Woodbury, and Daniele Mortari, Texas A&M University

The ability to observe resident space objects (RSOs) is a necessary requirement for space situational awareness (SSA). Observing satellites in the GEO belt is difficult using only ground based sensors because of their high altitude. Using space based cameras on satellites can provide an effective way of observing these satellites. The two methods proposed use either a single satellite in a circular orbit with a semi-major axis smaller than GEO and an inclination of zero degrees or a constellation of satellites at GEO.

08:50 **AAS 09 - 103** **Automatic Detection and Analysis of Non-evolutionary Changes in the Orbital Motion of Geocentric Objects**
Sergey Kamensky, Victor Stepanyants, and Andrey Tuchin, Vympel Corp., Moscow, Russia; Kyle T. Alfriend, Texas A&M University

An important part of the problem of spacecraft tracking and orbital parameter estimation is the task of automatically detecting and estimating executed maneuvers. Methods and algorithms for detecting and analyzing the non-evolutionary changes of the orbital motion caused by maneuvers are discussed in this paper. Three types of the non-evolutionary changes are investigated; one and two burn maneuvers, and low thrust maneuvers. Detailed descriptions of the algorithms for the maneuver parameters estimation and examples are presented in the paper.

09:15 **AAS 09 - 104** **Deriving Density Estimates Using CHAMP Precision Orbit Data for Periods of High Solar Activity**
Andrew Hiatt, Craig A. McLaughlin, and Travis Lechtenberg, University of Kansas

The extreme upper atmosphere including the thermosphere and exosphere is more variable than predicted by current density models. The variations not modeled in the atmospheric density have a significant effect on the ability to determine a satellite’s orbit resulting in potentially large errors in orbit predictions. This paper utilizes precision orbit data from the Challenging Minisatellite Payload (CHAMP) satellite as measurements in an optimal orbit determination process to generate density estimates during periods of increased solar activity. The results are compared with CHAMP accelerometer derived density for determining the accuracy of the density estimates derived from precision orbit data.

09:40 **Break**

10:05 AAS 09 - 105 GEOSAT Follow-On Precision Orbit Improvement through Drag Model Update

Stephen R. Mance, Craig A. McLaughlin, University of Kansas Aerospace Engineering Department; Matthew Wilkins, Schafer Corporation; Frank G. Lemoine and David D. Rowlands, NASA Goddard Space Flight Center; Paul Cefola, MIT Department of Aeronautics and Astronautics

This paper demonstrates the ability to improve orbit determination for GEOSAT Follow-On through updated drag modeling. This is accomplished by updating GEODYN, the NASA GSFC Precision Orbit Determination and Geodetic Parameter Estimation Program, with the NRLMSISE-00 density model and implementing density corrections found using dynamic calibration of the atmosphere. By doing so, orbit determination accuracy should increase, giving more accurate altimetry precision and thus a more accurate measurement of sea level. This improvement then can be applied to any low earth orbiting spacecraft requiring precision orbit determination.

10:30 AAS 09 - 106 On Preliminary Orbit Determination: A New Approach

Reza Raymond Karimi and Daniele Mortari, Texas A&M University, Aerospace Engineering Dept.

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

10:55 AAS 09 - 107 Comparison of Different Methods of LEO Satellites Orbit Determination For a Single Pass Through a Radar

Z. Khutorovsky, S. Kamensky, and N. Sbytov, “Vympel” Corporation, Moscow, Russia; Kyle T. Alfriend, Texas A&M University

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

11:20 AAS 09 - 108 Passive Multi-Target Tracking with Application to Orbit Determination for Geosynchronous Objects

Kyle J. DeMars, The University of Texas at Austin; Moriba Jah, Air Force Maui Optical and Supercomputing Site, AFRL

As telescope systems achieve greater photometric sensitivity and metric accuracy, the number of detected and tracked objects in deep space orbits around the Earth is likely to increase exponentially. The Pan-STARRS 1 (PS1) telescope, just now coming on line atop Mount Haleakala on the Island of Maui (at the Maui Space Surveillance System [MSSS]), will provide 19-24 visual magnitude sensitivity and sub arc-second metric accuracy for track-mode sensitive objects. A method is presented herein which combines Set-Hypothesis Tracking along with a Probability Data Association Filter in order to associate observed objects with existing tracks as well as initiate objects which are being observed for the first time.

Session 2: Rendezvous, Relative Motion, Formation Flight, and Satellite Constellations 1

Chair: Dr. Aaron Trask
Apogee Integration

08:00 **AAS 09 - 109** **A Cooperative Egalitarian Peer-to-Peer Strategy for Refueling Satellites in Circular Constellations**

Atri Dutta and Panagiotis Tsiotras, School of Aerospace Engineering, Georgia Institute of Technology

We propose a new Cooperative Egalitarian peer-to-peer (CE-P2P) refueling strategy for satellites in a circular constellation. The methodology uses a network flow formulation to determine the optimal CE-P2P maneuvers incurring the minimum amount of fuel during the ensuing orbital transfers. Since the methodology may yield sub-optimal solutions, we also provide estimates of sub-optimality of these solutions. We demonstrate the benefits of CE-P2P strategies when compared with previously P2P refueling alternatives (ie, CE-P2P, E-P2P and C-P2P).

08:25 **AAS 09 - 110** **An Investigation of Teardrop Relative Orbits For Circular and Elliptical Chief Satellites**

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

Relative satellite motion between a chief and deputy satellite in close proximity is well described by the Clohessy-Wiltshire equations which in more general form can accommodate chiefs in eccentric orbits. When the chief and deputy satellites have different periods, the resulting relative orbit drifts in the chief-fixed reference frame. Under most conditions these drifting relative orbits produce a teardrop trajectory that intersects itself, providing an opportunity to thrust and remain on the teardrop. This research presents a methodology for mission planners to evaluate candidate teardrops for chiefs in circular orbits and extends the teardrop concept to the elliptical case.

08:50 **AAS 09 - 111** **Control System Design and Simulation of Spacecraft Formations via Leader-Follower Approach**

Mahmut Reyhanoglu, Embry-Riddle Aeronautical University

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

09:15 **AAS 09 - 112** **Decentralized Optimization for Control of Satellite Imaging Formations in Complex Regimes**

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

Decentralized control and agent-based modeling techniques are explored in multi-body regimes to determine optimal spacecraft motion in formations with complex objectives. Cooperative satellite "agents" share a common objective (high resolution imaging) and simultaneously pursue private goals (minimal fuel usage). An algorithm is developed based on dual decomposition. An artificially decomposed primal problem is solved, replacing one computationally intractable formulation with many smaller tractable problems. The outcome from an agent-based model is compared to a simple, traditional, non-linear optimal control solution. Then, exploiting the reduced computational requirements, the agent-based model simulates arrays with increasing numbers of satellites and constraints.

09:40 **Break**

10:05 **AAS 09 - 113** **Electromagnetic Flat Docking System for In-Orbit Self-Assembly of Small Spacecraft**
Samia Smail and Craig Underwood, Surrey Space Centre

The paper presents a novel method of in orbit assembly of small Intelligent Self-powered Modules (ISMs). The self assembly is achieved using the Electromagnetic Flat Docking System (EFDS). Compared to other conventional docking mechanisms, the EFDS is a propellant-less docking adapter designed to control the motion of the ISMs during the final approach maneuvers. With its simple sensors and actuators, plume impingement is mitigated and precise alignment is not needed prior to initial contact. The electromagnets sizing is treated and the docking control methodology is studied. Maxwell and MATLAB simulations show the ability of the EFDS to bring two ISMs from a separating distance of 10 meters up to physical coupling.

10:30 **AAS 09 - 114** **Investigations of a Massive, Non-spherical Chief in Close Proximity Formations**
Cengiz Akinli and Ryan Russell, Georgia Institute of Technology

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

10:55 **AAS 09 - 115** **One-Dimensional Test Bed for Coulomb Controlled Spacecraft**
Carl R. Seubert and Hanspeter Schaub, Aerospace Engineering Sciences Department, University of Colorado, Boulder

This paper discusses the first results of a novel testbed to examine relative motion using electrostatic (Coulomb) forces. The concept uses active charge emission to control naturally occurring spacecraft potential. The testbed uses a non-conducting one-dimensional hover track which levitates charged craft. With two variable potential charged objects it is possible to actuate the suspended craft and study relative motion due to charge. The challenges of constructing an electrostatic actuation testbed in a terrestrial environment are outlined, including design, construction, and position sensing. Test data quantifies external disturbances and the testbed's ability to demonstrate electrostatic relative motion actuation.

Session 3: Spacecraft Guidance, Navigation, and Control 1

Chair: Dr. James Turner
TAMU Aerospace Eng.

08:00 **AAS 09 - 116** **Spacecraft Constellation Orbit Estimation via a Novel Wireless Positioning System**
Shu Ting Goh, Ossama Abdelkhalik, and Seyed Alireza (Reza) Zekavat, Michigan Technological University

A spacecraft relative position estimation that using a novel wireless communication has been proposed. Two scenario have been considered, two-spacecraft and three-spacecraft configuration. The relative distance, azimuth and elevation angles between two spacecraft are mesuremed by sensor; then, the Extended Kalman Filter is implement to update the estimation error. Effects of various parameters on the estimation accuracy have been study, including measurement noise, process noise covariance andnumber of measurement set. The further analysis and study on the orbital elements, and stability will be addressed in this paper.

08:25 **AAS 09 - 117** **A New Optimal Orbit Control for Two-Point Boundary-Value Problem Using Generating Functions**
Mai Bando and Hiroshi Yamakawa, Kyoto University

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

08:50 **AAS 09 - 118** **Improvement of Vision-Based Estimation Using Multiple Vector Observations**
Daero Lee and Henry Pernicka, Department of Mechanical and Aerospace Engineering, Missouri University of Science & Technology

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

09:15 **AAS 09 - 119** **Optimal Guidance for Lunar Ascent**
David G. Hull, University of Texas

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

09:40 **Break**

10:05 AAS 09 - 120 Desensitizing the Minimum-Fuel Powered Descent for Mars Pinpoint Landing
Haijun Shen, Hans Seywald, and Richard Powell, Analytical Mechanics Associates, Inc.

Desensitized Optimal Control (DOC) methodology is applied to the minimum fuel powered descent on Mars, in order to reduce the landing errors in the presence of perturbations. Unlike the conventional practice of designing separately the nominal trajectory and a feedback tracking controller, DOC strategy incorporates the two designs in synergy, with each benefiting from and compromising to the other. This results in a nominal control profile that is reshaped from the well-known maximum-minimum-maximum structure, without excessive compromise on fuel consumption. The closed-loop control is less likely to exceed the prescribed bounds, leading to higher tracking accuracy.

10:30 AAS 09 - 121 Finite Set Control Transcription for Optimal Control Applications
Stuart A. Stanton and Belinda G. Marchand, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin

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

10:55 AAS 09 - 122 Autonomous Optical Lunar Navigation
Brian Crouse and Renato Zanetti, The Charles Stark Draper Laboratory; Chris D'Souza, NASA Johnson Space Center; Pol D. Spanos, Rice University

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

11:20 AAS 09 - 123 Rigid Body Inertia Estimation with Applications to the Capture of a Tumbling Satellite
Daniel Sheinfeld and Stephen Rock, Stanford University

A compact and efficient method for rigid-body inertia estimation is presented which may be used for the case of a tumbling satellite. The method is general and may be used for any rigid body undergoing either torque-free or non-torque-free motion. Included will be a proof that demonstrates the conditions under which the inertias may be uniquely solved for, a geometric interpretation of the estimation problem which provides an intuitive understanding of the equations, and simulation results to demonstrate the viability of the method.

Session 4: Attitude Sensing, Estimation, and Calibration 1

Chair: Kenneth Williams
KinetX, Inc.

13:30 **AAS 09 - 124** **Partial Sphere Tracking Using Visual Snakes: Application to Spacecraft Pose Estimation**

Rajtilok Chakravarty and Hanspeter Schaub, Department of Aerospace Engineering Sciences, University of Colorado, Boulder

This paper investigates a vision based strategy to solve the relative pose problem by tracking four independent spheres whose relative geometry is known. The novel aspect is that only target segments are used to estimate the true apparent sphere center and radius. The vision sensor used is a camera whose position and orientation of the camera frame with respect to the object frame to which it is attached is known. The vision sensor is equipped with active deformable contour algorithms (visual snakes), the outputs of which are used in the proposed pose estimation algorithm. Compared to earlier work which looked at calculating the relative pose based line of sight measurements only, this paper also looks at incorporating depth estimates into the algorithm.

13:55 **AAS 09 - 125** **Fast Access and Low Memory Star Pair Catalog for Star Identification**

David D. Needelman, James P. Alstad, and Haytham M. Elmasri, The Boeing Company; Peter C. Lai, The Aerospace Corporation

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

14:20 **AAS 09 - 126** **The K-Vector ND and its Application to Building a Non-Dimensional Star-ID Catalog**

Ben Spratling and Daniele Mortari, Texas A&M University

A data structure and algorithm are presented for performing aligned orthogonal range-searches on multi-dimensional data. Average case analysis results are that range-search performance is found to be O(d+k)-time, which does not depend on the database size but on the database dimensionality (d) and on the number of entries found (k). Performance is compared to the quad-tree both in theory and by experiment for desktop-class processors. Application to constructing a star catalog for non-dimensional star identification is presented.

14:45 **AAS 09 - 127** **Performance of Spin-Axis-Attitude-Estimation Algorithms With Real Data**

Jozef van der Ha, Kyushu University, Fukuoka, Japan

The paper evaluates the performance of the Tanygin-Shuster algorithm for spin-axis attitude determination using actual satellite data. These data are taken from two satellites with very different orbit and attitude characteristics.The importance of the selection of suitable data intervals is emphasized because of the variations of measurement sensitivities and the presence of singularities.The performances are evaluated on the basis of the observed measurement residuals. The results show that the performances are strongly affected by the presence of unknown biases in the measurements.

15:10 **Break**

15:35 **AAS 09 - 128** **Time Tag Issues with Star Tracker and Gyro Data for ICESat Precision Attitude Determination**

Sungkoo Bae, Randy Ricklefs, Noah Smith, and Bob Schutz, Center for Space Research, The University of Texas at Austin

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

16:00 **AAS 09 - 129** **Using Quantum Search Algorithm in Future Spacecraft Attitude Determination**

Jack Tsai, F.Y. Hsiao, and Y.J. Li, Tamkang University, Taiwan, R.O.C.

In this paper we study the potential application of quantum search algorithm to the spacecraft navigation with focus on attitude determination. Traditionally the attitude determination is achieved by recognizing the relative attitude to the background stars using various sensors. Due to the massive celestial database star pattern recognition is a complicated job. We propose a new method of attitude determination by applying the quantum search algorithm to the search of a specific star or star pattern. The quantum search algorithm could search the specific data out of an unstructured database containing a number of N data in only O(sqrt(N)) steps. As a result, by taking the advantage of the powerful searching ability, we could acquire the spacecraft attitude rapidly for navigation, guidance and control.

16:25 **AAS 09 - 130** **Nonsingular Attitude Filtering Using Modified Rodrigues Parameters**

Christopher D. Karlgaard, Analytical Mechanics Associates, Inc.; Hanspeter Schaub, University of Colorado

This paper describes a singularity avoidance technique for attitude estimation problems using Modified Rodrigues Parameters (MRP). The singularity avoidance technique is based on the stereographic projection properties of the MRP set, and makes use of a simple mapping relationship between MRP representations. In addition to the state mapping, an additional mapping is provided to transform the state covariance matrix between these two representations. Under specific conditions, the first-order covariance mapping amounts an identity transformation. Second-order covariance transformations suitable for divided difference filtering are provided.

Session 5: IBEX Special Session

Chair: John Carrico
Applied Defense Solutions

13:30 **AAS 09 - 131** **Mission Design for the Interstellar Boundary Explorer Mission**
Michelle Reno, Austin Mission Consulting; Ryan Tyler, Orbital Sciences Corporation; Nathan Schwadron, Boston University; David McComas, Southwest Research Institute

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

13:55 **AAS 09 - 132** **Prelaunch Trajectory Design and Analysis for the IBEX Mission**
Mike Loucks, Space Exploration Engineering; John Carrico, Applied Defense Solutions; Ryan Tyler, Orbital Sciences Corporation

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

14:20 **AAS 09 - 133** **Prelaunch Orbit Determination Design and Analysis for the IBEX Mission**
John Carrico and Lisa Policastri, Applied Defense Solutions; Mike Loucks, Space Exploration Engineering

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

14:45 **AAS 09 - 134** **Trajectory Design Operations for the IBEX Mission**
Mike Loucks, Space Exploration Engineering; John Carrico, Marco Concha, and Timothy Craychee, Applied Defense Solutions

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

15:10 **Break**

15:35 **AAS 09 - 135** **Orbit Determination Operations for the Interstellar Boundary Explorer**
Lisa Policastri, John Carrico, and Timothy Craychee, Applied Defense Solutions; Tom Johnson and James Woodburn, Analytical Graphics, Inc.

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

16:00 **AAS 09 - 136** **Effect of IBEX Spinning Attitude on Doppler Observations**
James Woodburn, Tom Johnson, and Vince Coppola, Analytical Graphics, Inc.; John Carrico and Lisa Policastri, Applied Defense Solutions

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

Session 6: Orbit Dynamics 1

Chair: Dr. James Gearhart
Orbital Sciences Corporation

13:30 **AAS 09 - 137** **A Cubed Sphere Gravity Model for Fast Orbit Propagation**
Brandon A. Jones and George Born, University of Colorado, Boulder

The cubed sphere model was designed to represent the gravity field of a given body for faster orbit propagation when compared to other commonly used models. A discussion of the cubed sphere model is provided, along with current methods for deriving the model from the spherical harmonics. Models have been generated for both the Earth and the Moon, with gravity anomalies characterized given the spherical harmonic model as a reference. Resulting differences in orbit propagation when compared to the spherical harmonics, and the characterization of changes in the integration constant, are discussed.

13:55 **AAS 09 - 138** **A Nonsingular Approach in Satellite Theory**
Giorgio E. O. Giacaglia, University of Taubate, Brazil; Bob E. Schutz, University of Texas at Austin

Nonsingular differential equations for the variation of variables suggested by Lagrange for the motion of an artificial satellite under the influence of the Earth gravitational field are developed keeping the usual orbital elements. It is shown that no singularities are present in these equations except for the case of a retrograde equatorial orbit.

14:20 **AAS 09 - 139** **Analytic Construction of Circular Orbits in the Circular Restricted Three Body Problem With Small Mass Parameter**
Mohammed Ghazy and Brett Newman, Old Dominion University

In this paper, an analytic solution for motion of the third body in a circular orbit in the plane of motion of the two primaries is introduced for small mass parameter. In this case, the Jacobi function allows implementation of Legendre polynomials, and the Jacobi integral equation is reduced to the Legendre normal form of an elliptic integral. A closed form expression for the period of motion and for coordinates as functions of time are introduced. This solution can be used as a generating orbit for purposes of numerical or analytical continuation of periodic orbits in three body systems in which mass parameter is close but not equal to zero.

14:45 **AAS 09 - 140** **Bezier Representation of Analytical Functions**
Troy A. Henderson and Daniele Mortari, Texas A&M University

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

15:10 **Break**

15:35 **AAS 09 - 141** **Nearly Circular Equatorial Orbits of a Satellite about an Oblate Body with Atmosphere**

Thomas Carter, Department of Mathematics, Eastern Connecticut State University; Mayer Humi, Department of Mathematical Sciences, Worcester Polytechnic Institute

This paper studies nearly circular equatorial orbits of satellites in the gravitational field of an oblate body that includes the J2 term and Quadratic drag. We derive analytic expressions for the orbit of a satellite under these conditions even if the local atmospheric density is provided in tabular form. This work includes four distinct atmospheric density models. A closed-form solution of the orbit equation for each model is compared with the numerical integration of the exact orbit equation disclosing the accuracy of the analytic solution that follows from each model. The simulations reveal some highly accurate results.

16:00 **AAS 09 - 142** **PPKBZ9-A,SA Two Orbit Propagators Based on an Analytical Theory**

Juan F. San-Juan, University of La Rioja

In the context of general perturbation theories, we analyze the motion of an artificial satellite around an Earth-like planet perturbed by the first eight zonal harmonic coefficients. By means of two Lie trasformations and the KBM method we produce a second order theory in closed form of the eccentricity. Two orbit propagators are derived from the analytical theory. The first is completely analytical while in the second numerical methods are used to compute the transformation of variables. Prediction accuracy given by our orbit propagator programs was investigated by using data of different types of Earth and Mars satellites.

16:25 **AAS 09 - 143** **Restricted Evolution Strategies for Computing Periodic Orbits**

Alberto Abad and Antonio Elipe, University of Zaragoza. Spain

We propose the use of modern optimization techniques based on evolution strategies for computing periodic orbits. First, we convert the problem of finding periodic orbits into a problem of finding zeros of a non-negative function. Next, we apply to this problem the so called restricted evolution strategy (RES), which is a modification of genetic algorithms or evolution strategies. Some applications to the determination of frozen orbits in Astrodynamics are made.

Session 7: Low Thrust Mission and Trajectory Design

Chair: Dr. Ryan Russell
Georgia Institute of Technology

08:00 **AAS 09 - 145** **An Efficient Method for Computing Near-Optimal, Low-Thrust Earth-Orbit Transfers**
Craig A. Kluever, University of Missouri-Columbia

Optimizing low-thrust transfers is a challenging problem; in many cases, mission analysts need to quickly obtain multiple optimal trajectories. In this paper, we demonstrate a new low-thrust trajectory optimization method that can rapidly obtain minimum-time Earth-orbit transfers. The key feature is the use of a simplified Earth-shadow model which greatly reduces the computational burden of predicting the shadow entrance/exit angles, as well as reduces the sensitivity of the iterative search on the transient shadow conditions. Numerical results for several transfer problems are presented, and these near-optimal results show a good match with fully optimized trajectories with accurate shadow models.

08:25 **AAS 09 - 146** **Applications Of Constraint Stabilization to Low-Thrust Mission Design**
Iman Alizadeh and Benjamin Villac, University of California, Irvine

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

08:50 **AAS 09 - 147** **Design Concept and Modeling of an Advanced Solar Photon Thruster**
Bernd Dachwald, Aachen University of Applied Sciences; Patrick Wurm, RWTH Aachen University

The so-called Solar Photon Thruster (SPT) holds the potential of providing significant performance advantages over the flat solar sail. Existing SPT design concepts, however, do not consider shadowing effects and multiple reflections of highly-concentrated solar radiation that would inevitably destroy the gossamer sail film. We propose a novel advanced SPT design concept that does not suffer from these optical over-simplifications, but requires a more sophisticated mathematical description. We derive the equations that describe the thrust force and compare the performance of our new SPT design concept with respect to the existing ones and the conventional flat solar sail.

09:15 **AAS 09 - 148** **Design of Low-Thrust Lunar Pole-Sitter Missions**
Daniel Grebow, Martin Ozimek, and Kathleen Howell, Purdue University

Low-thrust trajectories, restricted to regions below the lunar south pole, offer long-duration south pole surveillance. A potential mission is comprised of many phases, including an Earth-to-Moon transfer and continual line-of-sight access to the south pole for one year. After a brief transit to the north pole, the spacecraft settles into a lunar orbit. The trajectory is designed using nonlinear programming and collocation to maximize the time over the poles while remaining inside a specified bounded region. The results indicate that constant access to the polar regions for extended periods may be achieved with a single spacecraft and a low-thrust engine.

09:40 **Break**

10:05 **AAS 09 - 149** **Dynamics of Two-Body Connected System Subject to Solar Radiation Pressure**

S. A. Agafonov, Moscow Bauman State Technical University, Russia; A. D. Guerman, University of Beira Interior, Portugal; G. V. Smirnov, University of Porto, Portugal

One of the possible ways to control the solar sail orientation is to change cm-cp offset by relative displacement of one part of the structure with respect to the other. So there appears a problem of orbital dynamics of a two-body connected system under the action of solar radiation pressure. We study dynamics of two rigid bodies connected by a spherical hinge. The system is subjected to solar radiation pressure. When unperturbed, the system moves along a circular heliocentric orbit maintaining its orientation to the Sun. We analyse the the coupled orbital and attitude dynamics.

10:30 **AAS 09 - 150** **Low-Thrust Control of Lunar Orbits**

Nathan Harl and Henry Pernicka, Missouri University of Science & Technology

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

10:55 **AAS 09 - 151** **Multiobjective Optimization of Low-Thrust Trajectories Using a Genetic Algorithm Hybrid**

Matthew A. Vavrina and Kathleen C. Howell, Purdue University

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

11:20 **AAS 09 - 152** **Trajectory to the Orbit Largely Inclined with the Ecliptic Plane by way of Electric Propulsion Delta-V Earth Gravity Assist (EDVEGA)**

Yasuhiro Kawakatsu, Hitoshi Kuninaka, and Kazutaka Nishiyama, ISAS/JAXA

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

Session 8: Orbit Dynamics 2

Chair: Dr. Felix Hoots
The Aerospace Corporation

08:00 **AAS 09 - 153** **Displaced Periodic Orbits With Low-Thrust Propulsion in the Earth-Moon System**

Jules Simo and Colin R. McInnes, University of Strathclyde

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

08:25 **AAS 09 - 154** **Fast Orbit Propagation without Solving Kepler Equation**

Daniele Mortari and Jeremy Davis, Texas A&M University; Christian Bruccoleri, StarVision Technologies Inc.

A predictor-corrector approach is used for orbit propagation without solving Kepler's equation. By linear o quadratic estimators the value of the eccentric anomaly is estimated under constant time interval constraint. This value is then corrected using a single Newton-Raphson or Halley iteration. Quadratic propagation and Halley correction provide a machine error level accuracy for any eccentricity, and for the elliptic, parabolic, and hyperbolic cases. The method has constant complexity (not iterative), does not require pre-computed data, and can be implemented in just few lines of code.

08:50 **AAS 09 - 155** **Gravitational Potential of a Massive Disk**

Antonio Elipe and Eva Tresaco, University of Zaragoza; Andres Riaguas, University of Valladolid

We study the dynamics of an infinitesimal particle moving under the gravitational field of a massive bidimensional circular plate, we will call it a disk. We will consider a circular plate on the plane Oxy of a Cartesian coordinate system with its center at the origin of coordinates. For this body, we compute its potential function in closed form, and analyze the dynamics of a particle attracted by it. After the analysis of symmetries, we find the possible equiliria, their stability, and make a systematic search of periodic orbits.

09:15 **AAS 09 - 156** **Identification of Non-Chaotic Terminator Orbits near 6489 Golevka**

Stephen B. Broschart, Jet Propulsion Laboratory, California Institute of Technology; Benjamin F. Villac, University of California, Irvine

Terminator orbits are an attractive class of quasi-periodic orbits for missions to small bodies because they exhibit stable behavior in the presence of a strong solar radiation pressure perturbation and robustness against uncertainty in the gravitational environment. Here, periodic terminator orbit families are found by continuation methods in a simplified dynamical model and bifurcation families identified. Using the periodic solutions as a starting point, long-term stability analysis is performed in a representative, high-fidelity dynamic model using the Fast Lyapunov Indicator measure of chaoticity. Regions of long-term stable, quasi-periodic motion associated with “stability islands” near the periodic orbit solution are identified.

09:40 **Break**

10:05 AAS 09 - 157 Lunar Analytical Theory for Polar Orbits in a 50-Degree Zonal Model

Sebastian Ferrer, University of Murcia; Martin Lara, Real Observatorio de la Armada

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

10:30 AAS 09 - 158 Computation and Applications of an Orbital Dynamics Symplectic State Transition Matrix

Yuichi Tsuda, Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency; Daniel J. Scheeres ,The University of Colorado at Boulder

This paper presents a numerical method of deriving the symplectic state transition matrix for arbitrary Hamiltonian systems. It provides the exact state mapping of the linearized Hamiltonian systems, preserving the symplectic structure that all Hamiltonian systems should possess by nature. The symplectic state transition matrix is expected to be applied to accurate, yet computationally efficient dynamic filters, long-term propagations of the motions of formation flying spacecraft and the eigenstructure/manifold analysis of N-body dynamics, etc., where the exact structure-preserving property is crucial. We present the derivation of the symplectic state transition matrix, and show several practical appliations to show the performance.

10:55 AAS 09 - 159 The IAU2000A and IAU2006 Precession-Nutation Theories and Their Implementation

Vincent T. Coppola and John H. Seago, Analytical Graphics, Inc.; David A. Vallado, Center for Space Standards and Innovation

The IAU 2000A precession-nutation theory relates the International Celestial Reference Frame to the International Terrestrial Reference Frame and has been effective since January 2003. In 2006, the IAU moved to adopt a more dynamically consistent precession model to complement the IAU 2000A nutation theory. This update – described as IAU2006 precession-nutation in the 2009 Astronomical Almanac – is effective January 2009. Since there are multiple numerical standards relating the ICRF and ITRF to within 1 mas, this paper discusses the impact of the various alternative (yet acceptable) ITRF-to-ICRF transformations. A preferred operational alternative is introduced that is computationally faster and preserves accuracy.

Session 9: Spacecraft Guidance, Navigation, and Control 2

Chair: Dr. Moriba Jah
Air Force Research Laboratory

08:00 **AAS 09 - 160** **Designing an Interplanetary Autonomous Navigation System Using Visible Planets**
Reza Raymond Karimi and Daniele Mortari, Texas A&M University

Duality exists between the problem of orbit determination from line-of-sight measurements and the problem of an interplanetary autonomous navigation system. Both problems want to estimate an orbit. However, in interplanetary navigation problem, the finite value of the speed light requires modification of the classic orbit estimation problem. Also the data were corrupted with noise to simulate the true measurements. This paper shows how to extend orbit determination methods of Gauss, Double-r, and the technique developed by the current authors when observing distant planets.

08:25 **AAS 09 - 161** **Guidance Strategy of Vertical Landing for Reusable Sounding Rocket**
Takayuki Yamamoto and Satoshi Nonaka, JAXA/ISAS

Reusable Sounding Rocket aims to be low in cost and to be high frequency of experimental opportunities by its reusability. And also, the enlargement of the flight profile flexibility could acquire the high qualities of the experimental conditions. This rocket vehicle is a fully reusable vertical take-off and vertical landing (VTVL) rocket vehicle. In landing phase, this vehicle makes a turnover maneuver from a nose-first entry attitude. This makes it possible to achieve the deceleration and soft landing by its main engine thrust. In this paper, the turnover maneuver is numerically simulated and then the guidance strategy is considered.

08:50 **AAS 09 - 162** **Optimal Autonomous Orbit Control of Remote Sensing Spacecraft**
Sergio De Florio and Simone D'Amico, German Aerospace Center (DLR)

This paper analyses the problem of the autonomous control of a satellite in Low Earth Orbit using an optimum controller. The type of controller considered is a standard Linear Quadratic Regulator. The driving orbit control requirement is to keep the satellite orbit within a maximum absolute distance of 20 m (1 sigma) from a sun-synchronous, phased and frozen reference orbit. The control action is realized by in-plane and out of-plane thrusts whose cost is minimized. The PRISMA dual satellite mission flight software development and test environment and the TerraSAR-X mission scenario are used as test-beds to validate the control algorithms.

09:15 **AAS 09 - 163** **Covariance Analysis for the Cassini Extended Tour**
Rodica Ionasescu, Peter G. Antreasian, Jeremy B. Jones, and Duane C. Roth, JPL

The accurate navigation of the primary Cassini tour around Saturn has resulted in excess propellant on board the spacecraft. This will allow further exploration of Saturn and its satellites. In order to assure the success of an extended mission, all aspects of the tour navigation have to be planned in advance. This paper describes the results of a covariance study that was undertaken to assess the navigational capabilities for the extended tour from an orbit determination point of view, to estimate pointing accuracies at all the flybys for science planning, and to establish a Delta-V budget for the errors associated with the maneuver execution.

09:40 **Break**

10:05 AAS 09 - 164 Pseudospectral Optimal Control Algorithm for Real-Time Trajectory Planning

Michael A. Hurni, Pooya Sekhavat, and I. Michael Ross, Department of Mechanical and Astronautical Engineering, Naval Postgraduate School

We present the development and implementation of a new Pseudospectral (PS) optimal control algorithm for autonomous trajectory planning and control of an Unmanned Ground Vehicle (UGV) with real-time information updates. The algorithm is presented and used to solve various scenarios including a dynamic problem in which the UGV mission is to traverse from an initial start point and reach the target point in minimum time, with maximum robustness, while avoiding both static and dynamic obstacles. The vehicle senses the local changes in the environment and continuously updates its global map before re-computing the control solution at each real-time solution update.

10:30 AAS 09 - 165 Reduced-Order Filtering for Precision Autonomous Lunar Navigation with the aid of Smart Sensors

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

Future autonomous and crewed lunar missions require accurate landing capabilities which are made possible by precision navigation algorithms with the aid of smart sensor technology. Smart sensors help to improve reliability and landing accuracy; however, these sensors also require extra parameters in the navigation filter to appropriately account for inherent cross-correlations, thus increasing the overall computational burden of the navigation algorithm. Due to the nature of the extended Kalman filter (the navigation algorithm considered here), the computational requirements scale with the square of the state size, thus indicating the need for a reduced-order filter which retains the robustness and performance of a full-order filter. Building upon previous developments of precision lunar landing navigation, a reduced-order filter design and analysis against a full-order design are presented.

10:55 AAS 09 - 166 Vision-Based Relative State Estimation Using the Unscented Kalman Filter

Daero Lee and Henry Pernicka, Department of Mechanical and Aerospace Engineering, Missouri University of Science & Technology

This paper presents a new approach to spacecraft relative attitude estimation and navigation based on the unscented Kalman filter which was implemented and evaluated for rendezvous and proximity operations. The use of the unscented Kalman filter requires propagation of carefully selected sigma points from the nonlinear system to map probability distribution more accurately than is possible using the linearization of the standard extended Kalman filter. This approach leads to faster convergence when using inaccurate initial conditions in attitude estimation and navigation problems. This method uses observations from a vision sensor to provide multiple line of sight vectors from the chief spacecraft to the deputy spacecraft. Because the observation equations associated with the vision sensor are coupled with the attitude matrix and the relative position vector,

Session 10: Attitude Dynamics and Control 1

Chair: Dr. Hanspeter Schaub
University of Colorado

14:45 **Break**

15:10 **AAS 09 - 168** **Pointing Performance Investigation of a Multiple Rigid Body Spacecraft**

Burak Akbulut, Turkish Aerospace Industries; Kemal Özgören, Mechanical Engineering Department, Middle East Technical University; Ozan Tekinalp, Aerospace Engineering Department, Middle East Technical University

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

15:35 **AAS 09 - 169** **Attitude Control using Magnetic Torquers**

Kikuko Miyata and Jozef C. van der Ha, Kyushu University

In this paper, we present a few attitude control methods for the 50 kg class satellite "QSAT" which is developed by Kyushu University. The control actuations are performed by the three-axis magnetic torquers. We divide the mission operations period into three main phases corresponding to the expected attitude pointing conditions. We construct different attitude control methods for each phase. Of most interest is the normal-mode phase for which we have developed 4 different methods. These control methods are discussed and their performances are evaluated in the paper.

16:00 **AAS 09 - 170** **Development of Control and Measurement System for the Three-Dimensional Reaction Wheel**

Yoji Shirasawa, University of Tokyo; Yuichi Tsuda, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)

This paper presents a development of an attitude control device called three-dimensional reaction wheel. This device consists of only one levitated spherical rotor which can rotate around arbitrary axes without mechanical contact between the stator. This leads to the reduction of the weight and space of the device, and the failure caused by the mechanical contact would be also reduced. To verify the feasibility of this attitude control system, some experiments are carried out. 3-DOF rotation of spherical rotor is measured with a new contactless method, and the control capability of the system is investigated.

16:25 **AAS 09 - 171** **Use of Taylor Expansions of the Inverse Model to Design FIR Repetitive Controllers**

Kevin Xu and Richard Longman, Columbia University, New York

Slight imbalance in rotating parts on spacecraft can produce vibrations that compromise the operation of fine pointing equipment. Repetitive control (RC) can in theory completely eliminate the influence of such periodic disturbances. A very effective RC design method based on optimization in the frequency domain was presented previously. It develops compensators that exhibited specific patterns of zero locations. This paper takes a different time domain approach and does a Taylor series expansions of the reciprocals of zero factors. The approach forms a different and effective time domain design method, and in addition explains the zero patterns from the frequency approach.

Session 11: Mission Design 1

Chair: Dennis Byrnes
Jet Propulsion Lab

14:45 **Break**

15:10 **AAS 09 - 172** **Maneuver Plans for the First ATV Mission**

Pierre Labourdette, Denis Carbonne, Eric Julien, and Fleur Chemama, CNES, French Space Agency; Gilles Kudo, Thales Services; Serge Laurent, ATOS-ORIGIN

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

15:35 **AAS 09 - 173** **Navigation Analysis of the Trajectory Correction Maneuvers on Approach to the Pluto Encounter for the New Horizons Mission, using LORRI Only**

Eric Carranza, Peter Wolff, and Kenneth Williams, Kinetx, Inc. Space Navigation and Flight Dynamics Practice

The most recent navigation studies for the statistical maneuvers in the Pluto Approach Phase of the New Horizons Mission have been documented. Included in this paper is a description of the effect of possible Trajectory Correction Maneuvers (TCMs) beginning 100 days prior to Pluto Closest Approach (C/A) to as close in as 10 days prior to C/A. Based on this analysis, a strategy of performing two maneuvers in the last 100 days prior to C/A is recommended by the Navigation Team. The latter TCM and its contingency are needed to achieve the B-plane target aim point at the nominal time.

16:00 **AAS 09 - 174** **New Horizons Pluto Approach Navigation: The Effect of Nix and Hydra on Time of Flight Knowledge**

D. R. Stanbridge, J. K. Miller, E. Carranza, B. G. Williams, and P. Wolff, KinetX Inc.

The New Horizons Mission to explore the Pluto system was launched in January 2006, encountered the Jupiter system in February 2007, and will arrive at Pluto in July 2015. This paper presents an updated Pluto orbit determination covariance study, incorporating the effects of Pluto's two newly discovered moons, Nix and Hydra. The Optical Navigation image schedule, utilized during approach, was updated. The addition of Nix and Hydra decreases the time of flight uncertainty due to their greater separation on the image plane compared to Pluto and Charon. Also presented are sensitivities to a-priori assumptions influencing the time of flight uncertainty.

16:25 **AAS 09 - 175** **Optimal Steering Strategy For a Gravity Tractor Mission To Deflect Asteroid 99942 Apophis Prior To Close Encounter With The Earth In 2029**

Dario O. Cersosimo and Craig Kluever, Department of Mechanical and Aerospace Engineering, University of Missouri

We examine the effectiveness of a quasi-optimal steering strategy for a Gravity Tractor mission to deflect asteroid 99942 Apophis from the possible passage through a keyhole in 2029 that will cause a resonant return and possible impact in 2039. Direct optimization of the thrust vector is compared against along track thrusting using patched conics. Results suggest that optimal steering might help to reduce tug times required to deviate Apophis from passage through a keyhole. However it does not contribute significantly when a deflection distance of the order of one Earth radii is needed to avoid direct impact with the Earth.

Session 12: Advanced Attitude Sensors Special Session

Chair: Dr. Brian Kawauchi
The Aerospace Corporation

08:00 **AAS 09 - 176** **The Hemispherical Resonator Gyro: From Wineglass to the Planets**
David Rozelle, Northrop Grumman Navigation Systems Division

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

08:25 **AAS 09 - 177** **Precision Navigation Sensors Based on Cold Atoms**
Mark Kasevich, Stanford University

Recent advances in the quantum-level control of atoms using light has resulted in the evolution of a new class of high performance inertial sensors, including accelerometers gyroscopes and gravity gradiometers. This talk will present basic operating principles and discuss performance of current and envisioned future generation sensors and systems. While the current generation of sensors has been developed for terrestrial applications, space-based implementations appear feasible and promising.

08:50 **AAS 09 - 178** **Integrated Ultracold Atom Chip Gyroscopes**
Dana Anderson, University of Colorado

Atom interferometers have a Sagnac sensitivity to rotation that is a remarkable eleven orders of magnitude greater than that for light. While considerable effort is still needed to reduce the total system size and improve performance, the core portion of ultracold atom systems is sufficiently small to be considered practical for space applications thanks to atom chip technology. Integrated systems offer the possibility of incorporating gyroscopes, accelerometers and clocks that utilize a common ultracold atom technology. This talk provides a brief overview of ultracold atom interferometry and the current status of ultracold atom gyroscope development.

09:15 **AAS 09 - 179** **Attitude Sensors on a Chip: Feasibility Study and Breadboarding Activities**
Franco Boldrini, Elisabetta Monnini, and Dorico Procopio, Selex Galileo; Bernard Alison, Thales Alenia Space France; Werner Ogiers, Independent consultant (formerly with Cypress Semiconductor and FillFactory nv); Manuel Innocent, Cypress Semiconductor Corp Belgium; Alan Pritchard, BAE Systems; Stephen Airey, European Space Agency

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

09:40 **Break**

10:05 AAS 09 - 181 The Joint Milli-Arcsecond Pathfinder Survey (JMAPS): Mission Overview
Bryan Dorland, Greg Hennessy, and Rachel Dudik, US Naval Observatory

The Joint Milliarcsecond Pathfinder Survey (JMAPS) is a Department of Navy bright star astrometric all-sky survey scheduled for launch in the 2012 timeframe. Mission objectives include a complete update of star positions for the 2015 epoch to accuracy levels of 1 milliarcsecond (5 nano-radians) for bright stars, demonstration of 10 milliarcsecond attitude determination, and 50 milli-arcsecond attitude control on-orbit. We will describe the general instrument design and expected performance. We will discuss how this new level of attitude determination accuracy will enable significant new mission capabilities, and will focus on one specfic application: long distance (50,000-100,00 km) formation flying.

10:30 AAS 09 - 182 Qualification of the APS based Star Tracker To be flown on the Alphabus Platform
Franco Boldrini and Dorico Procopio, Selex Galileo; Stephane D'Halewyn, Thales Alenia Space France; Daniele Temperanza, European Space Agency

Galileo started APS Star Tracker activities in 2002, within ESA contracts dedicated to secure the technology for their mission to Mercury (BepiColombo). The feasibility of a compact, light and rad-hard star tracker based on the HAS APS detector was demonstrated and a Prototype was delivered in 2006 to be flown in Q2-2009 as experiment on the PROBA-2 satellite.
In July 2008 Galileo successfully completed a full qualification campaign of the APS based AA-STR, dedicated to the ALPHABUS platform for GEO Telecommunication applications. A first batch of AA-STR FMs was already sold, confirming the market demand for this product.

10:55 AAS 09 - 183 Next Generation Inertial Stellar Compass
Tye Brady, Charles Stark Draper Laboratory, Inc.

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

Session 13: Rendezvous, Relative Motion, Formation Flight, and Satellite Constellations 2

Chair: Dr. Thomas Starchville
The Aerospace Corporation

08:00 **AAS 09 - 184** **Electrostatic Spacecraft Collision Avoidance Using Piece-Wise Constant Charges**

Shuquan Wang and Hanspeter Schaub, University of Colorado at Boulder

This paper deals with a scenario with two slow moving spacecraft tending to collide if no collision avoidance maneuver is applied. A three-Phase piece-wise constant Coulomb force maneuver is proposed to achieve a collision avoidance maneuver with a symmetric relative trajectory. This symmetric trajectory guarantees collision avoidance keeps the original relative motion direction and bounds the relative change in kinetic energy level. Starting from a simple circular transitional trajectory, the paper first presents an analytical solution to calculate a unique symmetric trajectory. Next a general symmetric trajectory programming strategy is developed. Four constraints are found to guarantee a symmetric collision avoidance trajectory, while five independent variables are required to solve the problem. This leaves one degree of freedom (DOF) which can be utilized to optimize

08:25 **AAS 09 - 186** **Formation Flying: Relative Orbits' Modelling and Control through Eulerian Orbital Elements**

Gabriella V.M. Gaias and Michéle R. Lavagna, Politecnico di Milano; Alexei R. Golikov and Michael Yu. Ovchinnikov, Keldysh Institute of Applied Mathematics.

This work deals with the dynamics of spacecrafts in formation. The relative motion is described through difference between Eulerian orbital elements of the deputy satellite with respect to the chief's ones. Eulerian orbital elements are defined from the constants of motion of the Intermediary Motion: they include perturbations till part of the 4th zonal harmonic of the Earth's gravity potential. A target relative motion insensitive up to the J3 is defined by matching the time variations of the Eulerian angular elements. Reconfiguration manoeuvres are performed by a relative orbit control where errors in the orbital elements are fed-back.

08:50 **AAS 09 - 187** **Formation Keeping and Maneuvering for Astronomical, Dual Spacecraft Formation Flying Missions**

Stefano Casotto, Enrico Lorenzini, and Francesca Panzetta, Università di Padova, Padua, Italy

Typical astronomical satellite missions maintain inertial pointing over extended periods. In the case of a distributed observatory made of an optical assembly and the detector assembly flying in formation, the challenge is to keep the formation aligned inertially within tight tolerances. We investigate an optimized strategy for acquisition, keeping and reconfiguration of the formation to satisfy an observational schedule. Simulations account for all relevant forces using differential corrections and Lambert targeting for coarse formation acquisition and Yamanaka-Ankersen formulation of relative motion approximation for fine acquisition and reconfiguration. Formation keeping is simulated based on a novel, powerful theorem in formation flying.

09:15 **AAS 09 - 188** **Perturbation Model for the High Elliptical Formation Orbits (HEO)**

Edwin Wnuk, Astronomical Observatory of the A. Mickiewicz University, Poznan, Poland

The paper presents an analytical model of the relative motion of satellites in a formation on HEO that include the influence of geopotential coefficients up to arbitrary degree and order, lunisolar effects and solar radiation pressure. Formulas for differential perturbations have been transformed to the form enabling their application to the high elliptical orbits. Values of the eccentricity function are obtained with use of a special procedure that enables stable calculations for all values of the eccentricity less than one. The presented model can by use for precise predictions of the relative motion of satellites in a formation.

Perturbation models were analyzed for different types of formation flying architectures, including in-plane and out-of-plane formations, and for different types of spacecrafts (with different area to

09:40 **Break**

10:05 **AAS 09 - 189** **Rotating Symmetries in Space: The Flower Constellations**

Martin Avendano and Daniele Mortari, Texas A&M University

Flower Constellations is a novel methodology to design axial-symmetric satellite constellations synchronized with a rotating reference frame (e.g., the Earth). These constellations highlight the existence of unexpected shape-preserving rigid-body objects rotating with specific angular velocities. In this paper, the fundamentals of Flower Constellations theory is revisited in a very general way, and new important parameters (integers and angles) to describe these constellations arise.

10:30 **AAS 09 - 190** **The Two-Dimensional Linearized Equations of Perturbed Relative Motion**

Julio C. Benavides and David B. Spencer, Department of Aerospace Engineering, The Pennsylvania State University

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

10:55 **AAS 09 - 191** **The Use of Satellite Constellations and Formations for Future Gravity Field Missions**

Brian Gunter, João Encarnação, and Pavel Ditmar, Delft Institute of Earth Observation and Space Systems (DEOS), Delft University of Technology

The monitoring of Earth’s gravity field from space has witnessed great progress through the launch of several dedicated satellite missions over the past decade. Nonetheless, there are still limitations to the current gravity field missions that might be overcome through the use of multiple sets of formation flying satellites, or even through the use of satellite constellations. The goal of this study will be to explore some of these potential options, in an attempt to provide some recommendations for future gravity field missions.

Session 14: Trajectory Design and Optimization 1

Chair: Dr. William Cerven
The Aerospace Corporation

08:00 **AAS 09 - 192** **Lunar Free Return Trajectory Generation**
Mark C. Jesick and Cesar A. Ocampo, University of Texas at Austin

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

08:25 **AAS 09 - 193** **Repeat Ground Track Methods for Earth Observation Satellites: For Use in Optimization Algorithms**
Sharon Vtipil and Brett Newman, Old Dominion University

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

08:50 **AAS 09 - 195** **Initial Trajectory Model for a Multi-Maneuver Moon to Earth Abort Sequence**
Cesar Ocampo and Robin Saudemont, The University of Texas at Austin

To support the mission and trajectory design problems associated with the Moon to Earth trajectories for the Crew Exploration Vehicle (CEV), we develop the starting trajectory model that serves as the first iterate for a complete targeting and optimization procedure that takes a spacecraft from any closed lunar parking orbit to the Earth entry interface state for any date. The motivation for this work is to examine the `any time abort' capability required for the CEV human Moon mission. The maneuvers are either impulsive or inertially fixed finite burns. An analytical procedure that constructs such trajectories is presented.

09:15 **AAS 09 - 225** **Flying by Titan**
Frederic J. Pelletier, Peter G. Antreasian, Shadan Ardalan, Kevin Criddle, Rodica Ionasescu, Jeremy Jones, Robert Jacobson, Daniel Parcher, Duane Roth, and Paul Thompson, Jet Propulsion Laboratory

The Cassini spacecraft encounters the massive Titan about once every month. These encounters are essential to the mission as Titan is the only satellite of Saturn that can provide enough gravity assist to shape the orbit tour, which will allow outstanding science for many years. From a navigation point of view, these encounters provide many challenges. In particular those that fly close enough to the surface for the atmospheric drag to perturb the orbit. This paper discusses the dynamics models developed to successfully navigate Cassini and determine its trajectory. This includes the moon’s gravity pull with its second degree zonal harmonics J2, the attitude control perturbations and the acceleration of drag.

09:40 **Break**

10:05 **AAS 09 - 198** **Optimal Trajectory Planning for Robotic Manipulators: Simulation and Experiments**

J. Cascio, M. Karpenko, P. Sekhavat, and I.M. Ross, Naval Postgraduate School

Motion planning for robotic manipulators is a challenging problem that continues to receive a great deal of attention. This paper demonstrates the applicability of pseudospectral optimal control to solve the motion planning problem for a multi-link robotic arm. Minimum cost point-to-point maneuvers in the absence and presence of workspace obstacles are considered and kinodynamic constraints are incorporated as part of the optimal control formulation. Both simulation and experimental results are presented to substantiate the applicability of the pseudospectral approach for robotic motion planning. Some of the advantages of pseudospectral methods over existing techniques in the robotics literature are also discussed.

10:30 **AAS 09 - 199** **Averaging and Mission Design: the Paradigm of Enceladus**

Martin Lara, Real Observatorio de la Armada; Jesús F. Palacián, Universidad Pública de Navarra; Ryan P. Russell, Georgia Institute of Technology

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

Session 15: Attitude Sensing, Estimation, and Calibration 2

Chair: Dr. Don Mackison
University of Colorado

13:30 **AAS 09 - 200** **Application of the Backward Smoothing Extended Kalman Filter to Attitude Estimation using Radar Observations**

Kyle C. Volpe and Zachary J. Folcik, MIT/ Lincoln Laboratory; Paul J. Cefola, Massachusetts Institute of Technology

The Backward Smoothing Extended Kalman Filter (BSEKF) is a type of Iterated Extended Kalman Filter (IEKF) developed by Mark Psiaki at Cornell University, for state estimation problems in which the dynamic and measurement equations are highly nonlinear. In his paper, Dr. Psiaki was able to demonstrate improved performance using the BSEKF for estimation problems with large initial attitude or attitude rate errors. The intent of this paper is to show that applying the BSEKF to an equally challenging attitude estimation problem using nontraditional measurements, in the form of radar imagery, yields significant accuracy and reliability improvements over a Batch Least Squares algorithm.

13:55 **AAS 09 - 201** **Estimation and Calibration of Alignment Change between Precision Star Sensors**

Takanori Iwata, Japan Aerospace Exploration Agency; Noboru Muranaka, CosmoLogic; Hoshiko Takayasu, NEC Aerospace Systems; Tetsuo Kawahara, NEC Corporation

As star sensors' accuracy is improved, alignment changes between star sensors are becoming a dominant factor preventing precise attitude determination. A precision star tracker was developed for the Advanced Land Observing Satellite (ALOS). On-orbit calibration of sensor alignments for the star tracker, however, revealed an anomaly affecting attitude determination accuracy. Orbit periodic changes and long-term temporal changes were observed in relative alignments between its optical heads. Those alignment changes were modeled and an approach to estimate them was developed. Periodical estimation of the alignment changes has been performed and derived alignments have been updated to ground-based attitude determination for compensation.

14:20 **AAS 09 - 202** **Extended Kalman Filter for MMS State Estimation**

Julie Thienel, US Naval Academy; F. Landis Markley and Rick Harman, NASA Goddard Space Flight Center

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

14:45 **AAS 09 - 203** **Gyro Misalignment Decomposition Applied to MESSENGER Calibration**

Mark E. Pittelkau, Aerospace Control Systems, LLC

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

15:10 **Break**

15:35 **AAS 09 - 204** **Further Study on Attitude Acquisition of a Satellite with a Partially-Filled Liquid Tank**

Ja-Young Kang, Korea Aerospace University; Victoria L. Coverstone, University of Illinois at Urbana-Champaign

In this study, an appropriate wheel spin-up strategy for a momentum transfer maneuver of a spacecraft with large internal slosh mass will be derived and nutation damping time constant will be determined for various parameter values. Those analyses will be based upon a minimum residual nutation angle. Also the study will focus on how liquid slosh mass influences the system properties such as moments of inertia in the time domain.

16:00 **AAS 09 - 205** **Kalman Filter Based Multimode Attitude Determination Algorithms for a LEO Satellite**

A. Kutlu, Turkish Aerospace Industries; O. Tekinalp, Middle East Technical University

This study presents the design of a Kalman Filter based attitude determination algorithms for a hypothetical LEO satellite with a multi-mode structure that employs different sensor combinations and as well as online switching between these combinations depending on the sensor availability. The performance and effectiveness of these different attitude determination modes and the multi-mode structure are investigated through simulations. Especially the accuracy of the state estimation and the behavior of the system covariance matrix on the mode transition phases will be presented.

16:25 **AAS 09 - 206** **Attitude Determination from Light Curves via Unscented Kalman Filtering**

Charles J. Wetterer, US Air Force Academy; Moriba Jah, Air Force Research Laboratory

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

Session 16: Flight Dynamics Operations and Spacecraft Autonomy

Chair: Dr. Michael Gabor
Northrop Grumman

13:30 **AAS 09 - 207** **Overview of ATV Flight Dynamics Operations from Separation to Docking**

Hélène Cottet, Laurent Francillout, and Jean-Jacques Wasbauer, CNES

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

13:55 **AAS 09 - 208** **Automated Transfer Vehicle (ATV) "Jules Verne" Flight: Real-Time GNC Monitoring at ATV-CC/FDS - Concepts and Mission Results**

Mauro Augelli, Pascale Ferrage, and Alejandro Torres, Centre National d'Etudes Spatiales (CNES); Christophe Veltz, EADS Astrium-ST

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

14:20 **AAS 09 - 209** **Management of Unforeseen Events by Flight Dynamics Team During ATV Jules Verne Operations**

Hélène Cottet, Laurent Francillout, Jean-Jacques Wasbauer, and Pierre Labourdette, CNES

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

14:45 **AAS 09 - 211** **Heuristic Approach for Satellite Mission Scheduling**

Soon-mi Han, Seung-woo Back, Kyeum-rae Cho, and Dae-woo Lee, Pusan National University, Busan Korea; Peter M. Bainum, Howard University; Hae-dong Kim, Korea Aerospace Research Institute, Korea

For mission scheduling, genetic algorithms and neural network algorithms are adapted to both solve problems and analyze results. Simple examples that are presented in this paper consist of a stack of satellite mission and its parameters. Main parameters and constraints of the missions include priority of the mission, cost, due date, weather, emergency request, time, energy balancing, and on board memory. The paper is presented under the premise that the array of all missions is presented in the order of time. MATLAB is used to implemented the algorithms to simulate the mission scheduling problem. The orbit propagation is performed by STK and mapped by MATLAB.

15:10 **Break**

15:35 **AAS 09 - 212** **Cooperative Control for Satellite Formation Reconfiguration Via Cyclic Pursuit Strategy**

Gianmarco Radice, Department of Aerospace Engineering, University of Glasgow; Tao Yang and Weihua Zhang, Department of Astronautics and Materials Engineering, National University of Defense Technology

This paper studies a methodology for group coordination and cooperative control of n agents to achieve reconfiguration tasks, i.e. formation radius enlargement and phase angle adjustment. The proposed approach is to separate the control law in two manifolds: planer movement control and orthogonal displacement suppression. The first is based on a cyclic pursuit strategy. For the other, a decentralized control law is integrated to maintain the circling center still. In orthogonal direction, a linear minus feedback control for displacement coupled with velocity rate is used. The local stability of the whole system is analyzed as well. Simulation examples are given to illustrate the efficacy of the proposed method.

Session 17: Optimization

Chair: Dr. Chris Ranieri
The Aerospace Corporation

13:30 **AAS 09 - 213** **An Adaptive and Learning Approach to Sampling Optimization**
Troy A. Henderson, Daniele Mortari, John L. Junkins, and Martin Avendano, Texas A&M University

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

13:55 **AAS 09 - 214** **Optimal Thrust Design of a Mission to Apophis Based on a Homotopy Method**
Xiaoli Bai, James D. Turner, and John L. Junkins, Texas A & M University

A novel homotopy method for solving optimal thrust direction control problems through Pontryagin's principle is presented. This method enforces the satisfaction of the dynamic equation constraints along the homotopy path, yielding an algorithm robust to the nonlinearity of both dynamic equation constraints and performance function. This approach extends the convergence domain of the initial guess of the unknown boundary conditions and is applied to an Earth to Apophis mission analysis. A hybrid impulsive and low thrust propulsion strategy is studied. We prove that the launch window for the mission can span a full year by using the hybrid strategy.

14:20 **AAS 09 - 215** **Applications of Non-Linear Constrained Optimization Methods and an Evolutionary Strategy on Low-Thrust LEO to Molniya and LEO to GEO Orbit Transfers**
Patrick S. Williams and David B. Spencer, Department of Aerospace Engineering, The Pennsylvania State University

Numerous types of low-thrust orbit transfers can now be achieved. Here, LEO to Molniya and LEO to GEO transfers are investigated and are optimized to achieve maximum efficiency in propellant while matching the final orbital elements target orbital elements. A robust optimization method with non-linear equality constraints is chosen to properly address these issues. However, the choice of optimization method is important, since some algorithms may lead to better or faster convergence. Both classical non-linear constrained methods and an evolutionary strategy are implemented in Satellite Toolkit's Astrogator®, in order to determine which methods produce the most desirable results.

14:45 **AAS 09 - 216** **Iterative Learning Control in Nonlinear Systems using State Estimation for Relinearizations**
Richard Longman, Columbia University, New York City; Katja Mombaur, LAAS-CNRS, Toulouse, France

Iterative learning control (ILC) applies to systems performing a tracking maneuver repeatedly. The error in each run is used to adjust the command in the next run, aiming to converge to zero error. Spacecraft applications include making fine pointing equipment follow a precise scan pattern in spite of flexibility effects. Previous papers showed how to use effective linear ILC laws in the neighborhood of a desired trajectory of a nonlinear system. This paper shows how to extend the range of convergence, by performing repeated relinearizations which requires simultaneous estimation of the state history.

15:10 **Break**

15:35 **AAS 09 - 217** **Modeling Perturbations and Operational Considerations when using Indirect Optimization with Equinoctial Elements**

Andrew Feistel and Christopher Ranieri, The Aerospace Corporation

Using equinoctial elements with indirect optimization methods, a generalized technique is developed to allow the effects of various orbital perturbations to be incorporated in the equinoctial force model and the corresponding co-state equations needed to generate optimal minimum time trajectories. Additionally, operational concerns are addressed to allow any mission-specific required coast arcs to be optimally placed for minimum time solutions that in preliminary designs never have coast periods. Results are presented showing the effects of various perturbations (third bodies, J2, solar radiation pressure) on GTO to GEO transfers and the implantation of optimally placed coast arcs.

16:00 **AAS 09 - 218** **Optimal Continuous-Thrust Orbit Transfers via Trade Space Exploration**

Daniel D. Jordan and David B. Spencer, Department of Aerospace Engineering, The Pennsylvania State University; Timothy W. Simpson, Department of Mechanical and Nuclear Engineering, Department of Industrial Engineering, The Pennsylvania State University; Michael A. Yukish and Gary M. Stump, Applied Research Laboratory, The Pennsylvania State University

Engineering design problems often contain correlations and tradeoffs that may or may not be obvious or well-understood. As the complexity increases, decision makers must grasp tradeoffs effectively. Trade space visualization tools allow an effective exploration of a design space and show the underlying tradeoffs and nuances particular to a specific problem. We apply our trade space visualization software to search for optimal constant low thrust and constant thrust acceleration spacecraft trajectories using a known optimal solution and explore the input space. A known optimal solution is used to explore the nearby input space to search for other optimal or near-optimal solutions. The problem is modified to include the discrete hardware-side design variable, engine type, and optimal solutions are found for each corresponding specific impulse.

16:25 **AAS 09 - 219** **Pseudospectral Based Hypersonic Vehicle Trajectory Optimization with Complex Aerothermal Constraints**

Timothy R. Jorris, Christopher S. Schulz, Farid Rafla, and Franklin R. Friedl, U.S. Air Force

Hypersonic vehicle reentry trajectories are traditionally formulated as a two-point boundary value problem which considers a variety of problem related path constraints. For extended endoatmospheric hypersonic flight, the total aerothermal heat and heat flux imparted on the flight vehicle becomes a critical path constraint to consider. Heat calculations used in these cases, however, tend to be simplified to closed form representation that solely considers stagnation heating to limit the constraint complexity. This paper evaluates the performance of the Gauss pseudospectral optimization method in generating long flight duration hypersonic vehicle trajectories considering complex aeroheating calculations as path constraints.

Session 18: Mission Design 2

Chair: Yanping Guo
APL

08:00 **AAS 09 - 220** **Orbit Mechanics About Small Asteroids**

D.J. Scheeres, Colorado Center of Astrodynamics Research, Department of Aerospace Engineering Sciences, The University of Colorado

Space missions to small solar system bodies must deal with multiple forces acting on the spacecraft, including perturbations from the gravity field, solar tide, and solar radiation pressure. Previous work has investigated these effects in isolation but has not considered their joint effect. In this paper a study of the joint effects of these forces will be given, relying on averaged solutions for each of these effects. In addition, a closed-form theory for the secular dynamics of a spacecraft subject to strong solar radiation pressure perturbations in orbit about an asteroid on an elliptic heliocentric orbit is derived and presented.

08:25 **AAS 09 - 221** **Applications of Chaoticity Indicators to Stability Analysis around Small Bodies**

Benjamin F. Villac, University of California, Irvine; Stephen Broschart, Jet Propulsion Laboratory

The characterization of regions of stable motion in the dynamical environment near an irregular small body is addressed using fast Lyapunov indicators in combination with periodic orbit families computations. In particular, the definition of the metric, integration time and coordinate system is adapted to fit the particularities of asteroid dynamics, such as the irregular shape, gravitational field and importance of the solar radiation pressure. The stability maps generated using this method allow mission planners to design trajectories near small bodies which are relatively insensitive to dynamical model perturbations and remain bounded without active station keeping strategies.

08:50 **AAS 09 - 222** **Pathfinding and V-Infinity Leveraging for Planetary Moon Tour Missions**

Adam Brinckerhoff and Ryan Russell, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology

The well established technique of V-infinity leveraging is applied to the planetary moon tour problem, and a global analysis of the related design space is approached using an automated pathfinding technique. This work primarily focuses on designing interior inner-moon transfers, and the task is accomplished using an algorithm that calculates the characteristics of each V-infinity leveraging maneuver, targets and optimizes specific leveraging maneuvers, and analyzes the resulting resonance hopping trajectories in a fuel versus time of flight Pareto front. Example numerical results are produced for orbital transfers between scientifically interesting moons in the Jovian and Saturnian systems.

09:15 **AAS 09 - 223** **Flight Path Control Design for the Cassini Equinox Mission**

Powtawche N. Williams, Christopher G. Ballard, Emily M. Gist, Troy D. Goodson, Yungsun Hahn, Paul W. Stumpf, and Sean V. Wagner, Jet Propulsion Laboratory, California Institute of Technology

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

09:40 **Break**

10:05 AAS 09 - 224 The Endgame Problem PART A: Vinfinity Leveraging Technique and the Leveraging Map

Stefano Campagnola, University of Southern California; Ryan Russell, GeorgiaTech

ESA and NASA renewed interest on missions to Europa, Ganymede and Titan poses the question on how to best solve the Endgame problem. Endgames typically aim at a cheap insertion maneuver into the science orbit, and can be designed using either Vinfinity Leveraging Maneuvers (VILMs) or the Multi-Body dynamics. In this paper we derive new formula for the VILM and build the Leveraging Map to compute the pareto front for Europa Endgames. We prove that the cost of a VILM sequence decreases when using high altitude flybys (as done in the Multi-Body technique). Finally we find a simple quadrature formula to compute the minimum DV transfer between moons using VILMs.

10:30 AAS 09 - 226 Invariant Manifolds, Discrete Mechanics, and Trajectory Design for a Mission to Titan

Evan S. Gawlik, Jerrold E. Marsden, and Ashley Moore, California Institute of Technology; Stefano Campagnola, University of Southern California

In this study, we explore the use of patched three-body models in conjunction with a discrete mechanical optimal control algorithm for the design of a fuel-efficient tour of Saturn’s moons. In contrast to utilizing traditional trajectory design models such as the patched conic approximation, we exploit subtleties of the three-body problem, a classic problem from celestial mechanics that asks for the motion of three masses in space under mutual gravitational interaction, in order to slash fuel costs. In the process, we demonstrate the aptitude of the DMOC (Discrete Mechanics and Optimal Control) algorithm in handling celestial mechanical optimal control problems.

10:55 AAS 09 - 227 The Endgame Problem PART B: The Multi-Body Technique and the T-P map

Stefano Campagnola, University of Southern California; Ryan Russell, GeorgiaTech

ESA and NASA renewed interest on missions to Europa, Ganymede and Titan poses the question on how to best solve the Endgame problem. Endgames typically aim at a cheap insertion maneuver into the science orbit, and can be designed using either Vinfinity Leveraging Maneuvers (VILMs) or the Multi-Body dynamics. In this paper we study the anatomy of the Multi-Body approach using a new graphical tool, the Tisserand-Poincare'(T-P) map. The T-P map gives a new insight on the Multi-body technique. It shows that ballistic Endgames are possible and it explains why we need multiple flybys even in the case of ballistic transfers. Finally we use the T-P graphs and those new concepts to implement a simple robust design method for endgame transfers.

Session 19: Orbit Determination 2

Chair: Dr. Paul Schumacher
Air Force Research Laboratory

08:00 **AAS 09 - 229** **ATV's Jules Verne On-Ground Orbit Determination**
Nicolas Delong, Isabelle Escané, and Mauro Augelli, CNES; Bruno Gerey and Adriana Martin, Coframi; Ludovic Labboz, Atos-Origin

The Automated Transfer Vehicle (ATV), developed by Astrium-ST for ESA, is unmanned automated vehicle to provide the ISS with different services. CNES has developed the ATV Control Centre under ESA contract and is responsible for the spacecraft operations. One of the control center's tasks is to perform on-ground orbit determination using GPS measurements. This paper discusses our operational software and process (Kalman and LSM) employed to perform absolute navigation, to initialize relative on-board GPS navigation, and to monitor relative navigation before docking. Operational result, post flight analysis, and compliance result with demonstration criteria and joint ATV-ISS flight rules are presented.

08:25 **AAS 09 - 230** **Development of the Technique for Covariance Prediction Using the Gravity Colored Noise**
Andrey I. Nazarenko, Space Observation Center; Kyle T. Alfriend, Texas A&M University

The conventional approach for obtaining the orbit uncertainty either does not consider the dynamic model errors or represents them with white noise. In the first case, the RMS of the prediction is underestimated. Attempts to represent the uncertainty by white noise have not yielded good results. This paper develops an approach for representing the gravity model uncertainties with colored noise. In contrast to other works the colored noise parameters are estimated as part of the orbit determination process. It is shown that it is necessary to take into account the mutual correlation of the state vector errors with colored noise.

08:50 **AAS 09 - 231** **Circular and Zero-inclination Solutions for Optical Observations of Earth-orbiting Objects**
Kohei Fujimoto, The University of Michigan; Jared M. Maruskin, The San José State University; Daniel J. Scheeres, The University of Colorado

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

09:15 **AAS 09 - 232** **Orbit Determination and Propagation of Objects With High AMR For Orbital Archive Maintenance**

Vladimir Agapov and Victor Stepanyants, Keldysh Institute of Applied Mathematics; Sergey Kamensky and Zakhary Khutorovskiy, Vympel Corp.; Kyle T. Alfriend, Texas A&M University

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

09:40 **Break**

10:05 **AAS 09 - 233** **Satellite Conjunction Monte Carlo Analysis**

Salvatore Alfano, Center for Space Standards & Innovation

This works uses a simplified Monte Carlo process to assess the satellite collision probability computations of various methods. Each object is assumed spherical and a time span is set about the initial TCA to bound the results. Two statistical bounding criteria are used to determine the minimum number of cases needed. The purpose is to assure the consistency of the Gaussian process from epoch to closest approach point. Because no unique or complicated force models are used the results can be easily repeated and independently validated.

10:30 **AAS 09 - 234** **Satellite Maneuver Detection: A Statistical Certainty Metric**

Kevin Stout, MIT Lincoln Laboratory and University of Texas at Austin; Zachary Folcik, MIT Lincoln Laboratory

Statistical certainty metrics provide insight into the size and likelihood of detected maneuvers. Results of using two different methods to construct certainty metrics are shown. The first method uses probability density functions and the second uses maneuver detection data from a set of detection criteria. Results for the certainty metric are shown for 17 satellites over a span of 500 days with 1349 known maneuvers and 110 known false alarms. As the maneuver size (delta V) increases over the interval from 0 to 0.4 m/s, the certainty metric yields a 58% increase in probability per 1 (m/s) delta V.

10:55 **AAS 09 - 236** **Satellite Orbit Determination Using Continuous Low-Thrust Modeling**

Zachary Folcik, MIT Lincoln Laboratory; Paul Cefola, Massachusetts Institute of Technology

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

11:20 **AAS 09 - 237** **Tracking Objects with Unknown Dynamics**

Drew Woodbury and Daniele Mortari, Texas A&M University

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

Session 20: Tethers

Chair: Dr. Thomas Lovell
AFRL

08:00 **AAS 09 - 238** **Deployment Control of Electrodynamic Tethers**

Paul Williams, Delft University of Technology; Steven Tragesser, University of Colorado at Colorado Springs

The deployment of electrodynamic tethers is important in future applications of conductive tethers in space. This paper introduces a strategy for deploying an electrically conductive tether. Instead of constraining the final libration dynamics to be zero at the end of deployment, the controller is designed to deploy the tether into a periodic solution for the in- and out-of-plane librations. Control over the current and rate of change of reel-rate is used to manipulate the deployment dynamics to intersect the terminal manifold created by the librational periodic solution. A feedback controller is also designed for stabilizing the tether librations around the periodic solution.

08:25 **AAS 09 - 239** **CE2: A CubeSat Electron Collector Experiment**

Bill Amatucci, Stephen Arnold, Shannon Coffey, George Gatling, Steve Huynh, Paul Jaffe, Bernie Kelm, Steve Koss, John McGahagan, and Adam Thurn, Naval Research Laboratory; Christopher Compton and Erik Tejero, SFA Inc.; Joe Carroll, Tether Applications Inc.; John Bowen and Jason Anderson, Cal Poly

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

08:50 **AAS 09 - 240** **Exploration of the Jupiter Plasma Torus With a Self-Powered Electrodynamic Tether**

Davide Curreli and Enrico C. Lorenzini, CISAS "G. Colombo" Università di Padova; Claudio Bombardelli, ESA Advanced Concept Team; Manuel Sanjurjo-Rivo, Fernando R. Lucas, and Jesus Peláez, Universidad Politecnica de Madrid; Daniel J. Scheeres, University of Colorado at Boulder; Martin Lara, Real Observatorio de la Armada Spain.

The two (stable) triangular Lagrangian points L4 and L5 of the Jupiter-Io system lye inside the Io's plasma torus and they acts as attractors for bodies co-orbiting along the Io's orbit. In the paper it has been demonstrated that an Electrodynamic Tether can be placed at a fixed distance from Io (and co-orbiting with it) away from a Lagrangian point by using the electrodynamic thrust produced through the interaction with Jupiter's magnetosphere and plasmapshere. While in this new equilibrium position, the tethered system generates k-WATTS of POWER that can be used on board the spacecraft.

09:15 **AAS 09 - 241** **Jovian Capture of a Spacecraft With a Self-Balanced Electrodynamic Bare Tether**

Manuel Sanjurjo-Rivo and Jesús Peláez, Universidad Politécnica de Madrid; Daniel J. Scheeres, University of Colorado at Boulder

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

09:40 **Break**

10:05 **AAS 09 - 242** **On the Thrust Capability of Spinning Electrodynamic Tethers Working in Generator Mode**

Claudio Bombardelli and Jesús Peláez, Tether Dynamics Group, School of Aeronautical Engineering, Universidad Politécnica de Madrid, Madrid, Spain.

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

10:30 **AAS 09 - 243** **Orbital Maneuvering with Librating and Spinning Electrodynamic Tethers**

Paul Williams, Delft University of Technology; Steven Tragesser, University of Colorado at Colorado Springs

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

10:55 **AAS 09 - 244** **Saturn Power Generation with Electrodynamic Tethers in Polar Orbits**

Claudio Bombardelli, Tether Dynamics Group, School of Aeronautical Engineering, Universidad Politécnica de Madrid, Madrid, Spain; Enrico Lorenzini, Department of Mechanical Engineering, University of Padua, Padua, Italy; Juan Sanmartin, Department of Applied Physics, School of Aeronautical Engineering, Universidad Politécnica de Madrid, Madrid, Spain

A power generation scheme based on bare electrodynamic tethers (EDT) working in passive mode is investigated for the purpose of supplying power to Saturn scientific missions. The system employs a spinning EDT on a low-altitude highly eccentric polar orbit which allows to efficiently convert plasmasphere energy into useful power. After optimising the tether design for power generation we compute the supplied power along the orbit and the impact of the Lorentz force on the orbital elements as function of the tether and orbit characteristics. The EDT power density is computed and shown to be greater than conventional power sytems.

11:20 **AAS 09 - 245** **Spin-Up and Deployment Control of a Tether Sling**

Steve Tragesser, University of Colorado at Colorado Springs; Bahman Gorjidooz, ITT Corp.

A tether sling holds tremendous promise as an energy storage device, permitting space transportation systems capable of injecting a large number of payloads with low incremental costs. This paper develops motor and deployment controls to go from rest to a desired final tether length and end velocity. Oscillations in the tether deployment angle are minimized in order to avoid additional tension in the tether. Control laws are developed for both power unlimited and power constrained cases.

11:45 **AAS 09 - 246** **Tether Deployment Modeling for the Sounding Rocket Experiment**

Paul Williams, Delft University of Technology; Hironori A. Fujii, Nihon University; Steven Tragesser, University of Colorado at Colorado Springs

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

Session 21: Attitude Dynamics and Control 2

Chair: Ryan Park
JPL

13:30 **AAS 09 - 247** **Application of SDRE Method to Design a Simulator Attitude Control System**

Rodrigo Guidoni Gonzales, Empresa Brasileira de Aeronáutica, Embraer, SJ Campos, SP, Brazil; Luiz Carlos Gadelha DeSouza, Instituto Nacionais de Pesquisas Espaciais – INPE, SJ Campos, SP, Brazil

This paper presents the application of State-Dependent Riccati Equation (SDRE) method to design a controller for the 3DoF DMC simulator. The SDRE can be considered as the non-linear counterpart of LQR control technique; therefore it has its advantage and disadvantages. In addition, practical applications also have to address problems like presence of noise in process and measurements and incomplete state information; Kalman filter is considered as state observer to address these issues and, in order to incorporate the non-linearities, SDRE method is also applied to filter implementation. A simulink-based model is implemented and a few simulations examples are provided to demonstrate the performance of the SDRE controller with SDRE-based Kalman filter.

13:55 **AAS 09 - 248** **Integrated Attitude Determination and Control System via Magnetic Measurements and Actuation Only**

Mohammad Abdelrahman, Astrodynamics and Control Lab., Department of Astronomy, Yonsei University, Seoul, Republic of Korea

A nonlinear control scheme using State–Dependent Riccati Equation SDRE is developed through a pseudolinearization of spacecraft augmented dynamics and kinematics. The full-state knowledge required for the control loop is provided through a generalized algorithm for spacecraft three-axis attitude and rate estimation based on the utilization of magnetometer measurements and their time derivatives, while the control torque is generated via magnetorquers. The resulted attitude determination and control system has shown the capability of estimating the attitude better than 5 deg and rate of order 0.03 deg/sec in addition to maintain the pointing accuracy within 5 degrees in each axis with pointing stability of less than 0.05 deg/sec.

14:20 **AAS 09 - 249** **Multiple Model Robustification of Iterative Learning and Repetitive Control Laws Including Design from Frequency Response Data**

Benjamas Panomruttanarug, King Mongkutt's University of Technology Thonburi, Bangkok, Thailand; Richard W. Longman, Columbia University, New York City; Minh Phan, Dartmouth College, Hanover, NH

Repetitive control (RC) and iterative learning control (ILC) aim for zero error in repeating situations. RC can eliminate the influence of slight imbalance in reaction wheels on fine pointing equipment, and ILC can aim for zero error in repeated scanning maneuvers. This paper extends previous works to show how three main classes of ILC can be made very much more robust to model errors, creating a cost function which results in the ILC law, and averaging it over samples from the model distributions. RC design directly from experimental frequency response data is also treated with similar results.

14:45 **AAS 09 - 250** **Novel Three-Axis Attitude Control Algorithms for Small Satellites Using Only Magnetic Actuators**
Mahmut Reyhanoglu and Sergey Drakunov, Embry-Riddle Aeronautical University

In this paper we present novel three-axis attitude control algorithms for small satellites using only magnetic torquers and investigate their performance through simulations. Since magnetic control systems are relatively lightweight, require low power and are inexpensive, they are attractive for small, inexpensive satellites in low Earth orbits. Although the magnetic torques that can be applied to the spacecraft for attitude control purposes are constrained to lie in the plane orthogonal to the magnetic field vector, three-axis magnetic stabilization is still possible as the variability of the magnetic field along the considered orbit is sufficient to guarantee the stabilizability of the spacecraft.

15:10 **Break**

15:35 **AAS 09 - 251** **Planar Maneuvering of a Spacecraft with Propellant Sloshing Using Switched Feedback**
Mahmut Reyhanoglu and Sergey Drakunov, Embry-Riddle Aeronautical University; Philip Savella, ITT Corporation

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

16:00 **AAS 09 - 252** **Satellite Attitude Control Using Dissimilar Redundant Actuators**
Ozan Tekinalp and Ozgur Kahraman, Middle East Technical University, Aerospace Engineering Department, Ankara, Turkey

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

Session 22: Trajectory Design and Optimization 2

Chair: Angela Bowes
NASA LaRC / Analytical Mechanics Associates

13:30 **AAS 09 - 253** **2 Dimensional, Energy Optimal Earth-Moon Trajectories**
Donghun Lee and Hyochoong Bang, KAIST: Korea Advanced Institute of Science and Technology, Department of Aerospace engineering

Optimal Earth-Moon trajectories are addressed in this paper. Cost function is related to energy level's fuel consumption of a low-thrust. Restricted three-body equations of motion are applied for the system dynamics, and continuously the low-thrust is used for the Earth escape trajectories, trans-lunar trajectories and Moon capture trajectories with no coast arcs. The contribution of this paper is to propose the design procedure of an optimal Earth-Moon trajectory using indirect method of full-scale, with no assumption.

13:55 **AAS 09 - 254** **A Formulation of Precision Translunar Trajectory Design**
Zhong-Sheng Wang, Embry-Riddle Aeronautical University

This paper describes a new design procedure to achieve precision translunar trajectory. Good insights can be gained from discussion of this procedure. The problem of designing a precision translunar trajectory is to find a trajectory from perigee to periselene that satisfies certain end conditions. An improved two-body analysis is used to find the approximate values of LAN, argument of perigee and perigee speed, then use contour graphs to find two sets of more accurate values, which are used in an iteration procedure to converge to the values that satisfy the end conditions (periselene altitude and lunar orbit inclination).

14:20 **AAS 09 - 255** **Variational Equations for a Generalized Spacecraft Trajectory Model**
Cesar Ocampo and Jean-Philippe Munoz, The University of Texas at Austin

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

14:45 **AAS 09 - 256** **Connecting Libration Point Orbits of Different Energies Using Invariant Manifolds**
Kathryn Davis, Rodney L. Anderson, and George H. Born, The Colorado Center for Astrodynamics Research, University of Colorado, Boulder; Daniel J. Scheeres, Department of Aerospace Engineering Sciences, University of Colorado, Boulder

This research presents a method for connecting libration point orbits of different energies using invariant manifolds. The initial and final orbits may be planar or three-dimensional. Close approaches of the unstable manifold of the initial orbit and the stable manifold of the final orbit are located and two deterministic maneuvers are used to connect the manifolds to form a final trajectory. Preliminary results indicate that this method produces fuel costs up to 68% less than transfers trajectories that do not employ the use of manifolds.

15:10 **Break**

15:35 **AAS 09 - 257** **Optimization of Spacecraft Trajectories: A Method Combining Invariant Manifold Techniques and Discrete Mechanics and Optimal Control**

Ashley Moore, Sina Ober-Blöbaum, and Jerrold E. Marsden, California Institute of Technology

By combining a low thrust mission design technique that uses invariant manifold techniques together with the optimal control algorithm DMOC, locally optimal, low thrust trajectories are generated. First, intersecting invariant manifolds of two planar, circular, restricted, 3-body problems are used to find an initial trajectory. Then DMOC adjusts this initial guess in the bicircular 4-body problem and optimizes it. This method is tested on a trajectory which begins in Earth orbit and ends in ballistic capture at the Moon.

16:00 **AAS 09 - 258** **Analysis and Implementation of In-Plane Stationkeeping of Continuously Perturbed Walker Constellations**

Jean A. Kechichian, The Aerospace Corporation

The station-keeping of Walker constellations is analyzed by considering the perturbations due to the Earth gravity field and the solar radiation pressure. These perturbations cause a differential drift effect that disrupts the symmetry of the constellation. The analysis considers a fictitious set of rotating reference frames that precess and move in the mean sense and drift with the average drift rate of all the vehicles. Fuel-efficient two-impulse rendezvous maneuvers are constructed to bring each vehicle to the center of its associated frame as soon as a user-defined tolerance band is violated.