Jan 23, 2006

Session 1: Attitude Dynamics & Control I

Chair: Professor Richard Longman
Columbia University

08:00 **AAS 06 - 100** **A New Attitude Maneuver using Kinematics and Dynamics of Non-Holonomic Turn**
Osamu Mori, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency

In this paper, new attitude maneuver using non-holonomic turn is proposed. The essence of this turn is characterized by an under-actuated system which does not have a direct torque device around the intended axis is made through what we call a coning motion. It is well known that falling cat motion utilizes non-holonomic turn. This paper shows the motion structure interpretation, in which a very interesting combination of kinematics and dynamics is found to govern the motion. This paper formulates not only turn motion but also 3-axes motions, and proposes a new control method for 3-axes maneuver of space robot.

08:25 **AAS 06 - 101** **Attitude Dynamics of Satellites Orbiting Asteroids**
Yulia Panchenko, McGill University, Montreal, Canada

The present paper is devoted to the investigation of the attitude dynamics of a satellite orbiting a uniformly rotating asteroid. The highly irregular shape of the asteroids along with their rotational states can lead to very interesting attitude dynamics. The equations of motion are derived for the three-dimensional motion of a satellite. Orbits corresponding to large 3D motions are identified and graphs illustrating the results are presented for Vesta, Eros and Castalia asteroids. Finally, it is demonstrated that the attitude dynamics of a satellite can be destabilized by a small eccentricity of the orbit.

08:50 **AAS 06 - 102** **Inflight Estimation of the Cassini Spacecraft's Inertia Tensor and Thrust Magnitude**
Antonette Feldman and Allan Y. Lee, Jet Propulsion Laboratory

Meeting the challenging requirements of the Cassini Attitude and Articulation Control Subsystem requires knowledge of the spacecraft's inertia matrix as well as thrusters' magnitude. This paper describes two methods used by the Cassini Attitude Control team to determine these key parameters and how flight telemetry was used to estimate them. By collecting data during multi-axis slews, we are able to generate a least-square estimate of the Cassini inertia tensor. A method for estimating the thrust magnitude based on Euler's equation is also discussed. Results of the applications of these methods on flight data will be given and discussed.

09:15 **AAS 06 - 103** **Three-axis Magnetic Attitude Control Using Pseudospectral Control Law in Eccentric Orbits**
Hui Yan, Kyle T. Alfriend, Texas A&M University

This paper is based on our previous paper for the magnetic attitude stabilization. Here we apply the pseudospectral control law to magnetic attitude control in eccentric orbits. Our results show three-axis magnetic attitude stabilization is achieved by using the pseudospectral control law via the receding horizon control in eccentric orbits. The residual librations errors are within 1 degree for the eccentricity 0.1.

09:40 **Break**

10:00 **AAS 06 - 104** **Direct Linearization of Continuous Dynamical Systems**
J.M. Jones,J.E. Hurtado, Texas A&M University;A.J. Sinclair, Auburn University

The quadratic form of the Lagrangian can be used to directly linearize the equations of motion for discrete dynamical systems. A method for directly generating linearized equations of motion is proposed for distributed parameter systems. The method presented requires only velocity-level kinematics to form the Lagrangian, dynamic potential, and equilibrium point(s) for the system. Select partial derivatives of the Lagrangian can then be computed and used to directly construct the linearized equations ofmotion for each equilibrium point. This method can greatly reduce the effort necessary to compute linearized equations of motion for continuous dynamical systems.

10:25 **AAS 06 - 105** **Parametric Optimization of Closed-Loop Slew Control using Interpolation Polynomials**
Sergei Tanygin, Analytical Graphics, Inc.

A recently introduced method for closed-loop slew control employed continuously updated 2-point osculating polynomials. This paper extends the method by reshaping the overall slew as a combination of smaller sub-slews that satisfy appropriate boundary conditions. Attitude and angular velocity at the end of each intermediate sub-slew enter the control law as parameters to be optimized.

10:50 **AAS 06 - 106** **Study of a Spacecraft Attitude Control based on an Onboard Simplified Radio Frequency System**
M Di Ruscio, F. Longo, L. Ascani, University of Rome

This paper presents a simple approach to the satellite attitude control using a single onboard transmitting system; this strategy reduces the complexity of the onboard equipment.
All the subsystem providing the attitude information and the control strategy are placed at the ground segment level. The transmitting part of the sensor, located on the spacecraft, consists of a dual baseline antenna system; each baseline consists of two antennas driven by properly modulated and coded signals. The described attitude control system is able to provide the information on attitude angles with an accuracy of few tenth of a degree.

Jan 23, 2006

Session 2: Attitude Estimation

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

08:00 **AAS 06 - 107** **Star Tracker Misalignment Calibration for the ICESat Mission**
Sungkoo Bae, Charles Webb and Bob Schutz, The University of Texas at Austin

To achieve its required laser-pointing accuracy of 1.5 arcseconds, the Ice, Cloud and land Elevation Satellite (ICESat) carries on-board a uniquely designed Stellar Reference System (SRS). Its restricted operation after launch, however, necessitated significant changes in ground-based precision attitude determination (PAD) algorithms. This paper compares two different methods used to correct variations in the instrument star tracker (IST) alignment. One depends on direct measurements of the IST motion, as observed by the SRS, while the other employs differences between two attitude determination methods. In addition, the original PAD methodology is re-examined, using improved simulation data derived from real-data experience.

08:25 **AAS 06 - 108** **Kalman Filter Design for JWST Spacecraft Attitude Determination System**
Peter C Lai, Sung K Park, Frank C Tung, Northrop Grumman Space Technology

This paper describes an 8-state Extended Kalman Filter (EKF) design for the James Webb Space Telescope (JWST) fine pointing mode attitude determination. Due to the stringent pointing requirements imposed on JWST, the single star measurement from the fineguidance sensor (FGS) in the telescope is incorporated into the typical two star tracker based spacecraft attitude determination system. However, the tower type structure of the large telescope is subject to thermal deformation and post-slew vibration.Therefore, the FGS alignment has to be calibrated during the flight. A simple covariance analysis is used to assess the effectiveness of this 8-state EKF. Various results are presented.

08:50 **AAS 06 - 109** **Planet or Moon Image Processing for Spacecraft Attitude Estimation**
Keun Joo Park, Korea Aerospace Research Institute; Daniele Mortari, Texas A&M University

This paper presents the summary of the image processing of the vision-based three-axis attitude determination sensor, which observes a solar system oblate body such as a planet or a planet's moon. From the observed image it is possible to extract two independent directions and, consequently, to estimate the three-axis spacecraft attitude. By measuring two independent directions, the sensor can operate in a stand-alone configuration. In this paper, algorithms to determine the required parameters using theobserved image are described.

09:15 **AAS 06 - 110** **Advances in Attitude Determination With Redundant Inertial Measurement Units**
Mark E. Pittelkau, Aerospace Control Systems, LLC

Key results of several recent papers on attitude determination and calibration with Redundant Inertial Measurement Units (RIMU) are summarized, and some subtleties are illuminated. A RIMU, which has more than three angular rate sense axes, offers enhancedsystem performance in terms of availability, reliability, redundancy, and accuracy. We discuss how to exploit the analytical redundancy of the RIMU to maximize the potential performance of a spacecraft system. Some of the observability properties that result from analytical redundancy are demonstrated via simulation. It is shown that calibration accuracy can be partially maintained even in the absence of attitude measurements.

09:40 **Break**

10:00 **AAS 06 - 111** **Sensing Element Evaluation for the JIMO Sun Sensor**
Sergei Jerebets, Jet Propulsion Laboratory

Different solar cell technologies are discussed with respect to recent radiation data on existing space solar cells to select a potential sun sensor sensing element to operate in the severe Jovian environment.

10:25 **AAS 06 - 112** **Structured Observability for Skewed Redundant IMU Filtering**
Robert M. Rogers, Rogers Engineering & Associates, Gainesville, FL

Attitude estimation and sensor calibration for a Skewed Redundant Inertial Measurement Unit (SRIMU) consisting of four gyros is considered and simulation results presented. Current literature suggests a least-squares method for combining the outputs fromall of these sensors to form an equivalent body rotation vector with an accompanying null space sensor level observation to insure system error observability. Rather than this least-squares combination, this paper considers outputs from groups of threegyros, each group used to implement its solution for attitude as well as a Kalman filter formulation that allows for individual gyro error estimates without the need for an additional sensor level observation. Four such filters are established and estimates from these filters are combined into an overall estimator.

10:50 **AAS 06 - 113** **Symplectic Attitude Estimation for Small Satellites**
Valpiani, James and Palmer, Phil, Surrey Space Centre

A novel method for efficient high-accuracy satellite attitude estimation is presented. Symplectic numerical methods are applied to Extended Kalman Filter (EKF) algorithms to create the SKF, which is shown to outperform the standard EKF in the presence ofnonlinearity and low measurement noise in the 1-D case. Building on this result, a six-state SKF is compared to an EKF of the same order for satellite attitude estimation. Simulation of a small satellite mission demonstrates orders of magnitude improvement in state accuracy and preservation of constants of motion. This new method shows promise for improved attitude estimation onboard resource-constrained small satellites.

Jan 23, 2006

Session 3: Mission Analysis I

Chair: Dennis Byrnes
Jet Propulsion Lab

08:00 **AAS 06 - 114** **Abort Options for Human Lunar Missions Between Earth Orbit and Lunar Vicinity**

Gerald L. Condon, NASA/Johnson Space Center; Juan S. Senent, University of Texas at Austin; Eduardo Llama, GB Tech

Apollo mission design emphasized operational flexibility that supported premature return to Earth. However, it was tailored to use expendable hardware for short expeditions to low-latitude sites and cannot be applied directly to an evolutionary program requiring long stay times at arbitrary sites. This work establishes abort performance requirements for representative on-orbit phases of missions involving lunar orbit/lunar surface rendezvous and libration point rendezvous missions. This study submits reference abort delta-V requirement and other Earth return data (e.g., entry speed, flight path angle) and also examines the effect of abort performance requirements on propulsive capability for selected vehicle configurations.

08:25 **AAS 06 - 115** **Analysis of Manipulator Operations for Orbiter Tile Repair**

Elizabeth M. Bains, NASA/ JSC; Rose M. Flores,Kwun Ki Siu, Billy G. Draeger, Jacobs-Sverdrup ESCG

Proposed methods of repairing the tiles on the Space Shuttle while on-orbit rely on the Shuttle and/or International Space Station (ISS) robotic manipulators. This paper discusses three analyses done of two proposed repair methods. One method uses theShuttle manipulator to maneuver the Shuttle relative to the ISS to present the Orbiter tiles to the ISS. An EVA astronaut then uses the Space Station manipulator as a platform for repair operations. The second method uses a 50 foot boom attached tothe Shuttle manipulator as a platform.

08:50 **AAS 06 - 116** **Approximations of Distant Retrograde Orbits for Mission Design**

Anil N. Hirani, University of Illinois; Ryan P. Russell, Jet Propulsion Laboratory

Distant retrograde orbits (DROs) are stable periodic orbits that exist in the circular restricted three body problem. Since no closed form solutions exist we present methods for approximating a family of planar DROs for an arbitrary, fixed mass ratio. Furthermore we give methods for computing the first and second derivatives of the position and velocity with respect to the variables that parameterize the family. The approximation and derivative methods described allow a mission designer to target specific DROs or a range of DROs with no regard to phasing in contrast to the more limited case of targeting a six-state only.

09:15 **AAS 06 - 117** **Characterization of Feasibility, Methods, and Requirements for Lunar Mission Abort Trajectories**

E. David Beksinski Jr., Ryan P. Starkey, Mark J. Lewis, University of Maryland

With NASA's exploration architecture it is certain that this Crew Exploration Vehicle (CEV) will take on a capsule type similar to the Apollo missions. Although many contingencies are planned; any unforeseen circumstances can induce emergency situations.The feasibility of a direct abort must be defined. An astrodynamic model for lunar transfer is required to allow for characterization of the abort feasibility envelope for any conceivable transfer orbit. In addition the model would allow for several trade-off studies involving differently staged abort options, factoring in fuel margins, to better define design requirements for the CEV regarding abort feasibility.

09:40 **Break**

10:25 **AAS 06 - 118** **The Mars Telecommunications Orbiter. A Key Asset in the Mars Network**
Fernando Abilleira, Jet Propulsion Laboratory

The Mars Telecommunications Orbiter (MTO) to be launched in 2009 will play a key role in the Mars Network since it will be the first interplanetary mission whose primary objective is to provide communications to existing and upcoming Mars missions. This paper presents a basic description of the primary mission and provides trajectory information for the Mars Telecommunication Orbiter. This overview of the MTO mission should be considered preliminary. (Note from the author: The MTO project was cancelled inJuly 2005).

10:50 **AAS 06 - 119** **Preliminary Aerothermodynamic Trajectory Analysis Framework for Planetary Entry Vehicles**
Prabhakar Subrahmanyam, San Jose State University

SPARTA is an Aerothermodynamic, Two dimensional, Structured, Compressible, Navier-Stokes flow solver. It is a platform independent and Graphical User Interface driven tool. A Trajectory framework has been developed to study the aerodynamic heating and todo preliminary trajectory analysis. This framework is linked to a planetary probe Relational Database Management System for comparative data analysis capability. A fourth order Runge-Kutta integration is employed for trajectory calculations. Empirical correlations for stagnation point heat transfer have been modeled using Fay-Riddell and Sutton-Grave correlations. The purpose of this research was to investigate the aerothermodynamics of atmospheric vehicles and to provide a computational trajectory database framework and flow field analysis for such vehicles.

Jan 23, 2006

Session 4: Formation Flying I

Chair: Dr. Thomas Lovell
AFRL

13:30 **AAS 06 - 120** **Analysis and control of convenient orbital configuration for formation flying missions**
Marco Sabatini, Giovanni Palmerini, Università La Sapienza; Dario Izzo, European Space Agency

Formation flying does require the identification and computation of spacecraft orbital control strategies demanding a suitable amount of thrusting action. Availability of reference trajectories which are less sensitive to orbital perturbation could be agood starting point. The paper investigates the nature of a set of convenient LEO orbits recently identified and their possible selection as reference for formation flying missions. Formation keeping effort is evaluated comparing different approaches as LQR and potential function methods. The particular configuration chosen ensures the practical interest of the results obtained.

13:55 **AAS 06 - 121** **Autonomous Satellite Formation Flying for the PRISMA Technology Demonstration Mission**
Eberhard Gill, Oliver Montenbruck, Simone d'Amico, Deutsches Zentrum für Luft- und Raumfahrt (DLR); Staffan Persson, Swedish Space Corporation (SSC)

PRISMA is a technology demonstration mission for the in-flight validation of sensor technologies and guidance, navigation and control strategies for spacecraft formation flying. It originates from an initiative of the Swedish National Space Board and theSwedish Space Corporation.
The paper focuses on PRISMA's navigation system as well as the guidance strategy and control approach. Using a high-grade GPS receiver, onboard orbit determination will provide absolute and relative position accuracies of 2 m and 0.5 m. The Spaceborne Autonomous Formation Flying Experiment will demonstrate a fully autonomous, robust and precise formation flying making use of an eccentricity/inclination vector separation.

14:20 **AAS 06 - 122** **Constraint Based Control Method for Precision Formation Flying of Spacecraft**
Try Lam, Jet Propulsion Laboratory; Aaron Schutte, The Aerospace Corporation; Firdaus E. Udwadia, University of Southern California

Control and station keeping of spacecraft in formation flying are explored in this paper. We propose a very general control methodology based on the general equations of motion for constrained systems to solve the problem of precision formation flying, resulting in a virtual platform. This paper demonstrates the method by applying the theory to the control of multiple spacecraft flying in precise formation around Mars. The examples include a 2-spacecraft leader-follower configuration and a 4-spacecraftrhombus configuration. In addition, we explore the effects of other constraints on formation flight, such as inclination constraints and time-varying relative distance constraints.

14:45 **AAS 06 - 123** **Coulomb Spacecraft Voltage Study due to Differential Orbital Perturbations**
Christopher Romanelli, Arun Natarajan, Hanspeter Schaub, Virginia Tech; Lyon King, Gordon Parker, Michigan Tech

The effects of differential atmospheric drag, J2 perturbations, and solar radiation drag on the relative motion of a small formation of satellites is examined. A study is also provided to compute Lorentz force acceleration of a charged spacecraft in Earth's magnetic field. Two formation types are considered when computing nominal spacecraft voltages to compensate for these perturbations. First, using a traditional formation flying approach all spacecraft are allowed to interact with each other. Second, a gluon-deputy craft combination is studied to illustrate how the required gluon charge levels will vary with different gluon radii, as well as different Debye lengths.

15:10 Break

15:30 AAS 06 - 124 The relative position control system design in formation flying satellites using super-conducting magnets

Ryosuke Kaneda, The university of Tokyo; Shin-ichiro Sakai,Hirohumi Saito, JAXA

The authors propose the novel formation flight control method using electromagnetic force with super-conducting magnets (SCM). Without any propellant, this electromagnetic force can control the relative position between two satellites. So, mission lifetime is not limited associated with the finite fuel supply. We assume that satellites orbit in LEO. SCMs should be excited by sinusoidal current in order to avoid the disturbance torque by the Earth magnetism. Therefore, proposed control method is basedon the phase difference in coil currents. The position control system is designed, and then evaluated with numerical simulations and experiments in this paper.

15:55 AAS 06 - 125 Stationkeeping for Leader-Follower Satellites in an Elliptical Orbit

Daero Lee, J. E. Cochran, Jr., Auburn University

In this paper, the orbital dynamics describing the relative motion of a leader satellite and follower satellite are considered. Equations are derived that describe the the relative motion when both satellites move in perturbed elliptical orbits that nominally are the same orbit. Control of the separation angle of the two satellites is addressed by considering the motion of each satellite with respect to its nominal motion.

16:20 AAS 06 - 126 Fusing Inertial and Relative Range Measurements for Inertial Navigation in the Presence of Large State Error Covariances

Paul J. Huxel, Dr. Robert H. Bishop, The University of Texas at Austin

This investigation examines the robustness of the extended Kalman filter (EKF) when simultaneously processing inertial and relative range measurements. It has been shown that processing relative range measurements in conjunction with inertial range measurements can directly increase the accuracy of the inertial state estimate. However, it has also been shown that in the presence of relatively large state error covariances the addition of relative measurements can cause an otherwise convergent filter to diverge. This study considers several methods for preventing this divergence, as well as in depth examination of second order terms to explain the basis of the problem.

16:45 AAS 06 - 127 Time Minimization reconfiguration for formation flying subject to several constraints

Liu Jian-feng, Rong Si-yuan, Cui Nai-gang, Harbin Institute of Technology, China

In the present paper the problem with respect to reconfiguration for satellites flying in formation subject to several constraints of collision avoidance 、 final configuration、energy equalization and so on is addressed. A method for optimalformation reconfiguration is introduced in view of time minimization using nonlinear programming technique (NLP), thus further this method is based on finding a solution to the system of nonlinear equations that arise from the first order necessary conditions for an extremum of the NLP problem.

Jan 23, 2006

Session 5: Orbit Mechanics I

Chair: Dr. Felix Hoots
AT&T

13:30 **AAS 06 - 128** **Semianalytical Propagation of Satellite Orbits About An Arbitrary Central Body**

Paul J. Cefola, Consultant and Research Affiliate at MIT

Precision mean element (PME) satellite theories play a key role in orbit dynamics analyses. These theories employ nonsingular orbital elements, comprehensive force models, Generalized Method of Averaging, and Numerical interpolation concepts. The DraperSemianalytical Satellite Theory (DSST), whose development was led by the author, and the independently-developed Universal Semianalytical Method (USM) are examples of such theories. The production of high degree and order gravity models for central bodies other than the Earth is now a reality. Consider the 165 x 165 model for the lunar gravity field, the 80 x 80 model for the Mars gravity field, and the 180 x 180 model for the Venus gravity field.

13:55 **AAS 06 - 129** **An Efficient Strategy for Targeting Ballistic Lunar Capture Trajectories**

Paul Griesemer, University of Texas at Austin

An efficient, robust method of targeting Ballistic Lunar Capture trajectories is described. The Sun-Earth restricted three body problem is used as an approximation of the Sun-Earth-Moon restricted four body problem to formulate an initial trajectory withproperties that are consistent throughout the family of Ballistic Lunar Capture trajectories. The initial guess is then applied to the Sun-Earth-Moon four body problem. By targeting parameters in the Earth-Moon rotating frame using a differential correction algorithm with analytical gradients, a captured lunar orbit is produced.

14:45 **AAS 06 - 130** **Spacecraft Formation-Keeping Using Closed-Form Orbit Propagator and Optimization Technique**

Tae Soo No, Jae Gye Lee, Chonbuk National University, Republic of Korea; John E. Cochran, Auburn University

In this paper, a simple method for modeling the relative orbital motion of and formation-keeping control strategy for multiple spacecraft flying is presented. Power series and trigonometry functions are used to approximately express the relative orbital motion between the member spacecraft. Then, this closed-form orbit propagator and optimization technique is used to plan a series of impulsive maneuvers, which maintain the formation configuration within the specified limit. As an example, formation-keeping of four spacecraft is selected. The motion projected onto the local horizontal plane (along-and cross-track plane) is a circle where the leader satellite is located at the center and other follower satellites are positioned circumferentially.

15:10 **Break**

15:30 **AAS 06 - 131** **Finding Ballistic Captures around Europa**
Drescher K., Getachew, Z., Lutz, S., To, L., UCLA; Lo, M.W., Villac, B.F., Jet Propulsion Laboratory

A tool to analyze ballistic capture dynamics around Europa in the planar, circular, restricted three-body problem is presented. It is based on the computation of the transit time of the trajectories intersecting two concentric circles around Europa. It allows us to find initial conditions for (finite time) ballistic capture trajectories at some distance from Europa while controlling the minimum periapsis altitude and the capture time. The consideration of the whole flow also results in placing the ballistic captures in their dynamical environments and relating them to the stable manifolds of some key unstable periodic orbits: the Lyapunov family and the unstable distant retrograde orbits. These two families of trajectories are shown to dominate the ballistic capture dynamics at different ranges of energies.

15:55 **AAS 06 - 132** **Families of Low-Energy Lunar Halo Orbit Transfers**
Jeffrey S. Parker, University of Colorado; Martin W. Lo, California Institute of Technology

This study presents several families of low-energy ballistic transfers to lunar Halo orbits. These transfers implement invariant manifold pathways to transfer from an initial LEO parking orbit to a final lunar Halo orbit using only a single injection maneuver. The ballistic transfers require about 100 more days, but 15% less energy, than conventional Hohmann transfers. Mission designers may be able to use these families of transfers to quickly perform trade studies and construct a ballistic lunar transfer with the orbital parameters useful to their particular mission.

16:20 **AAS 06 - 133** **Very low-thrust optimal transfers from GTO to GEO**
Jesús Gil-Fernandez, Lorenzo Tarabini, Mariella Graziano, GMV SA, Spain

A new hybrid direct/indirect optimization algorithm is presented to compute the minimum-time transfer from GTO to GEO, including phasing with desired SC. Very-low thrust results in several hundreds of revolutions to perform the large change in orbital elements. The optimal control solution of the fast-evolution problem combined with a direct method for the secular trajectory avoids the numerical instability arising from the very long propagations, decreases the computational time, reduces the sensitivityto the initial guess and provides a feasible transfer at every optimization step. Two trajectories are presented, subsynchronous (apogee constrained below GEO altitude) and supersynchronous (free apogee altitude).

16:45 **AAS 06 - 134** **Implementation Issues Surrounding the New IAU Reference Systems for Astrodynamics**
David Vallado, Analytical Graphics Inc.

The realizations of celestial and terrestrial reference systems have grown increasingly accurate in recent years, due to advancements in observational technology. Because of its extremely high precision, implementation of the latest IAU-2000 reference systems may pose numerous challenges for users accustomed to the former systems. This paper reviews the relevant IAU resolutions, presents summary equations, discusses accuracy and timing, examines nomenclature necessary to discuss the new reference systems,and offers recommended practices for implementation. Examples are provided to demonstrate the numerical test results and the precision differences between various implementations.

Jan 23, 2006

Session 6: Orbit Determination

Chair: Bob Glover
AT&T

13:30 **AAS 06 - 135** **A Nonlinearity Measure for Estimation Systems**
Andrew J. Sinclair, Auburn University, John E. Hurtado, John L. Junkins, Texas A&M University

The concept of nonlinearity measures for dynamical systems is extended to estimation systems, which include both a dynamical model and a measurement model. For linear systems, propagation through linear dynamics and update by linear measurements both preserve the Gaussian property of a distribution of estimates. For nonlinear systems, how well a Gaussian distribution of estimates stays Gaussian is identified as a measure of the nonlinearity in the total estimation system. This measure can be used to compare the nonlinearity introduced by both the dynamics and the measurements for various representations of a system.

13:55 **AAS 06 - 136** **Uncertainty Control Utilizing Natural Dynamics in Hamiltonian Systems**
F.Y. Hsiao, Tamkang University; D.J. Scheeres, University of Michigan

This paper investigates the feasibility of uncertainty control using the natural dynamics in Hamiltonian Systems with applications to spacecraft dynamics. According to Gromov's non-squeezing theorem, there exists a fundamental constraint on uncertainty propagation. In this paper we first review the previous results on the realization of non-squeezing theorem. Then the dynamical mapping of the uncertainty ellipsoids can be constructed with the algorithm developed in our previous works. Using this approachwe can determine whether a certain state of uncertainty is controllable or not. At the end a linear time invariant system is provided as an application of our current work.

14:20 **AAS 06 - 137** **Angles-Only Orbit Updates for Low Earth Satellites**
Chris Sabol, Air Force Maui Optical and Supercomputing; Kyle T. Alfriend, Texas A&M University; David Wiese, University of Colorado

This paper will provide the development of the analytical model for predicting the along-track error uncertainty and error uncertainty growth rate for the single-pass, angles-only orbit update, the validation of that model using real data cases, a summaryof efforts made to characterize the uncertainty of general perturbations based element sets, and conclusions on the practical expectations of the single-pass, angles-only orbit update using general perturbations based element sets.

14:45 **AAS 06 - 138** **Determination of Clustered Satellite Maneuvers Via Relative Motion**
Jill Tombasco, Chris Sabol, Air Force Research Laboratory; Tara Storch, SWC, Schriever AFB; Doug Presley, US Air Force Academy.

This research investigates the possibility of estimating maneuver time, magnitude, and direction based on relative motion within satellite clusters, with estimate accuracy depending on the amount of observation data available and intial manuever guess. The model utilizes differential right ascension and declination observations along with Hill's relative motion equations. Five co-located satellites were observed using a Raven telescope at the Air Force Maui Optical and Supercomputing (AMOS) site. The maneuver estimation varied both three dimensionally and without the radial maneuver component. A comparison of predicted and estimated maneuvers validates this estimation model as an asset to space situational awareness.

15:10 **Break**

15:30 **AAS 06 - 140** **In-Orbit Identification of Drag-Free Satellite Dynamics**

Stephan Theil, Center of Applied Space Technology and Microgravity, ZARM, University of Bremen, Germany

Drag-free control is one of the enabling technologies for future scientific space missions.This new key technology allows to reduce the residual accelerations on experiments on board satellites significantly. In order to achieve this very low disturbanceenvironment (for some missions < 1.0E-14 m/s²) the Drag-Free Control system has to be optimized. This optimization process is required because of uncertainties in system parameters which demand a robustness of the control system. The paper will presentan approach for the in-orbit identification of a drag-free control system. The discussion includes the modeling, possible excitation signals as well as simulation results.

16:20 **AAS 06 - 141** **Atmospheric Drag Model for Cassini Orbit Determination During Low Altitude Titan Flybys**

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

On April 16, 2005, the Cassini spacecraft performed its lowest altitude flyby of Titan to date, Titan-5, flying 1027 km above the surface of Titan. Not only was it an excellent opportunity to observe the effect of atmospheric drag from Titan on the OD solution, it was found early on that the drag needed to be modeled to get an accurate flyby solution. Different solutions will be compared against OD performance in terms of the flyby B-plane parameters, spacecraft thrusting activity and drag estimates. Results will be presented for Titan-5 as well as the most recent low altitude Titan-7 flyby.

16:45 **AAS 06 - 142** **Long Arc Analysis of GPS Orbits**

Laurent Froideval and B.E Schutz, The University of Texas at Austin

The influence of gravitational and nongravitational forces on the orbits of GPS satellites is well known. Although the gravitational forces are the dominant factors in characterizing long term orbital evolution, the uncertainties associated with modelingnongravitational forces are the dominant factors that limit the accuracy of long term predictions of GPS satellite positions. In this study, different models of solar radiation pressure were studied for the determination of GPS orbits. The results were compared to the daily IGS ephemerides. The observed characteristics may have implications for future navigation satellite systems.

Jan 24, 2006

Session 7: Attitude Dynamics & Control II

Chair: William Cerven
The Aerospace Corporation

08:00 **AAS 06 - 143** **Converting Repetitive Control into Stable Learning Control by Iterative Adjustment of Initial State**
Benjamas Panomruttanarug and Richard W. Longman, Columbia University

Iterative Learning control and repetitive control aim to converge to zero tracking error in repeating situations, using the error from the previous repetition to adjust the command in the next run. Repetitive control eliminates error from periodic disturbance, and can be used to isolate fine pointing equipment from vibration sources on satellites. Learning control allow high speed, high accuracy repeated tracking. Methods are developed that allow easily designed repetitive controllers to apply to the finite time learning control problem. Iterative adjustment of the initial state is used to establish convergence.

08:25 **AAS 06 - 144** **Tuning and Performance of Robust Multiple-Period Repetitive Control**
Richard W. Longman, Columbia University; Joe W. Yeol, Polytechnic University, NY, Yeong S. Ryu, New York City Collegte of Technology, NY

Fine pointing equipment mounted on a satellite, such as a telescope, must be isolated from vibration sources, such as a momentum wheel, reaction wheels, and CMG's. Newly developed methods in repetitive control (RC) allow RC to address multiple unrelated periods in a disturbance, obtaining zero error in the presence of the disturbance. The effectiveness of these methods is investigated for the spacecraft application. The ability to obtain robustness to residual modes, the adjustment of the learning gains for different periods, the ability to handle similar periods as in CMG's, and the ability to handle drifting periods that cross, are investigated.

08:50 **AAS 06 - 145** **Analysis and Demonstration: A Proof-of-Concept Compass Star Tracker**
M. Swanzy, D.Mortari, J.Hurtado, J. L.Junkins, Texas A&M University

Star sensors are typically used as attitude determination instruments on spacecraft orbiting Earth. This research utilizes the basic functionality of the star sensor in a new way: the orientation information from the star image is used to determine a user's latitude and longitude coordinates on Earth. This concept allows users to determine their position autonomously. This research analyzes and demonstrates the local position determination problem on Earth using a novel instrument, the Compass Star Tracker. Special focus is given to the mathematics of local position determination, an error source analysis, and the experimental tests that validate the position determination concepts.

09:15 **AAS 06 - 146** **Development of a damping mechanism for a spacecraft simulator**
Andre Hauschild, Christopher D. Hall, Virginia Tech

The equations of motion of a rigid air-bearing spacecraft simulator with attached spring mass damper are developed and linearized. The resulting stability conditions are used to establish design parameters for a damping mechanism for the spacecraft simulator. The conditions for an optimal damper working on earth are found from numerical analysis. The resulting design of a spring-mass damping mechanism for use on the spacecraft simulator is described, and its experimental performance is investigated and compared with the predicted performance.

09:40 **Break**

10:00 AAS 06 - 147 Analysis of Thrust Vectoring Capabilities for the Jupiter Icy Moons Orbiter

Konstantin Gromov, Marco B. Quadrelli, Emmanuell Murray, Jet Propulsion Laboratoy

This paper describes a strategy to mitigate the impact of trajectory design for the baseline Jupiter Icy Moons Orbiter on attitude control design. Rather than using the entire reaction control system to steer the spacecraft, we investigate the potential utilization of only thrust vectoring of the main ion engines for the required attitude control to follow a representative trajectory. This study identifies some segments of a representative trajectory where the required control torque exceeds the designedion engine capability, and how the proposed mitigation strategy succeeds in reducing the attitude control torques to within the existing ion engine capability.

10:25 AAS 06 - 148 Localization on Small Body Surface by Radio Ranging

Sayaka Higo, University of Tokyo, Tetsuo Yoshimitsu, Ichiro Nakatani, Institute of Space and Astronautical Science (ISAS), JAXA

Small body planets including asteroids and comets are full of geographical features as asteroid ITOKAWA has shown this September. To navigate the rover to the goal, precise localization is required. However, usual positioning methods are useless on smallbody planets. In this paper, we propose an effective localization method for a rover on a small body surface. It use Range measurement between a rover and a mother spacecraft. To confirm the accuracy and localization speed, formalization and simulation analysis are conducted. The simulation result showed the effectiveness of the proposed method: the rover localized within 6[m] for 6 hours observation.

10:50 AAS 06 - 149 Performance Analysis of Control Algorithms for FalconSat-3

Paul C. Tisa, Cadet, United States Air Force Academy

FalconSat-3 is the United States Air Force Academy's first attempt at three-axis attitude determination and control. This requirement is a product of the payloads the satellite will carry to conduct research for the US Department of Defense. The main focus of this paper is to test the implementation and performance of a number of controllers on a computer simulation. In the end, while many of the control algorithms could be used to meet FalconSat-3's attitude control requirements, proper integration ofthe B-dot, spin rate, and cross product law controllers yielded the best balance between competing performance characteristics.

Jan 24, 2006

Session 8: Optimization I

Chair: Victoria Coverstone
University of Illinois

08:00 **AAS 06 - 150** **A Simple Technique for Low-Thrust High-Accuracy Trajectory Optimization**
I. Michael Ross, Qi Gong, Naval Postgraduate School

Multi-revolution very low-thrust trajectory optimization problems have long been considered difficult problems due to their large time scales and high "granularity" of the corresponding trajectories. By relating this difficulty to the well-known problem of aliasing in the discrete Fourier transform, an anti-aliasing trajectory optimization method is developed. This method is remarkably simple and efficient in that it is based on first principles, and can easily be implemented on an on-board computer forclosed-loop space guidance. This paper will also prove and demonstrate that a high accuracy solution is a natural consequence of this method.

08:25 **AAS 06 - 151** **Autonomous Pseudospectral Knotting Methods for Space Mission Optimization**
I. Michael Ross, Qi Gong, Naval Postgraduate School

Dynamic optimization theory provides a formal framework to solve a large number of mission planning problems such as those encountered in libration point missions, formation design and control, asteroid missions and many others. These problems are hybrid: that is, they involve both continuous and discrete variables. The pseudospectral knotting method provides a unified framework for solving these problems. A long-standing problem in this approach has been the need for human intervention in deciding thenumber and location of these knot points. This paper develops an autonomous technique for addressing this problem towards the goal of allowing mission planners to focus on the operational aspects of the problem rather than clever mathematical tricks involving specialists.

08:50 **AAS 06 - 152** **Automating Trade Studies for Optimal Interplanetary Electric Propulsion Missions**
Prashant Patel, University of Michigan

Conducting preliminary trade studies are critical in determining the feasibility of a mission and identifying how various spacecraft systems will scale. We develop an algorithm for automating trade studies for electric propulsion interplanetary missions.This paper optimizes trajectories with constant-power, solar-power, variable specific impulse, and constant specific impulse low thrust propulsion systems. Technological parameters and the launch vehicle are integrated into the cost function allowing formaximization of the payload mass fraction. The cost function is dimensionless to allow for scaling of the systems without having to resolve the optimal control problem.

09:15 **AAS 06 - 153** **Constrained Trajectory Optimization for Lunar Landing**
Alisa M. Hawkins, Thomas J. Fill, Ronald J. Proulx, Draper Laboratory; Eric M. Feron, Massachusetts Institute of Technology

As a first step towards exploration of Mars and beyond, humanity will again be landing on the surface of the Moon. The increase in computational capability since Apollo allows more capable on-board G&C algorithms to be implemented, both for manned and unmanned missions. This paper explores the trade-space of fuel-optimal trajectories from a Lunar parking orbit to soft landing, constraining both translational and attitude states in selected phases of the decent trajectory. A Legendre pseudospectral methodis used to discretize and optimize the entire trajectory. Operational constraints include continuous thrust during braking, de-orbit perigee height specifications, and final vertical descent.

09:40 **Break**

10:00 AAS 06 - 154 Global optimisation of Multiple Gravity Assist interplanetary missions
Dario Izzo (ESA/Advanced Concepts Team)

In this paper we study the Multiple Gravity Assist (MGA) interplanetary transfer as a global optimisation problem and we discuss on its complexity. We introduce a space pruning technique of both time and space polynomial complexity. The space pruning technique introduced is then used in connection with an heuristic global optimisation method called Differential Evolution to produce globally optimal interplanetary trajectories. We show how a reliable global optimisation is achievable in this case also whenlaunch windows of the order of decades and a large number of swingby are considered. We then briefly touch upon the low-thrust arc problem and its possible implementation in the framework introduced and upon the MGA asteroid deflection problem.

10:25 AAS 06 - 155 Interplanetary Mission Design Using Differential Evolution
Aaron D. Olds, Craig Kluever, University of Missouri-Columbia; Michael L. Cupples, Science Applications International Corporation

A new trajectory design tool is introduced which uses a global optimization routine to identify optimal high-thrust interplanetary trajectories. The global routine, Differential Evolution, uses a population of randomly distributed solutions that interactin a way that resembles the evolution of living creatures. The method is shown to quickly and precisely find the best solution to missions with multiple gravity assists and deep space maneuvers, as well as round trip surface missions involving ellipticalparking orbits. No initial guesses are required to start the optimization. A statistical analysis of the solutions is provided for a number of case studies.

10:50 AAS 06 - 156 Primer Vector Theory Applied to Global Low-Thrust Trade Studies
Ryan P. Russell, Jet Propulsion Laboratory

Remarkably, the low-thrust spacecraft trajectory problem can be reduced to only a few dimensions using calculus of variations and the well-known Primer Vector Theory. This low dimensionality combined with the extraordinary speed of modern computers allows for rapid exploration of the parameter space and invites opportunities for global optimization. Accordingly, a general low-thrust trade analysis tool is developed based on a global search for local indirect method solutions. The result is a global Pareto front of mass optimal solutions for a full range of flight times. The method is tested on multi-revolution transfers in the Jupiter-Europa Restricted Three Body Problem.

Jan 24, 2006

Session 9: Formation Flying II

Chair: Dr. Hanspeter Schaub
Virginia Polytechnic Institute

08:00 **AAS 06 - 157** **Formation Control with Relative Information/Propagation Structure**
Takanao Saiki, The Institute of Space and Astronautical Science(ISAS)/JAXA

In formation flight missions, it is very important to control the relative positions of members. In order to keep the formation strictly and to avoid the collisions, the feedback control with the relative information between the members is effective. In this control, the information propagation structure (adjacency relation) of the formation as well as the local control law of each spacecraft determines the behavior of the formation. In this study, the information propagation structure of the formation isfocused on and how the information propagation structure influences the behavior of the formation is investigated.

08:25 **AAS 06 - 158** **Decentralized, Low-Communication State Estimation and Optimal Guidance of Formation Flying Spacecraft**
Dan Dumitriu, Sónia Marques, Pedro U. Lima, Instituto de Sistemas e Robótica, Instituto Superior Técnico, Portugal; Bogdan Udrea, ESA/ESTEC, Netherlands

This paper presents an integrated approach to GNC of formation flying spacecraft. The Navigation algorithm estimating the full relative state of all the spacecraft is a full-order decentralized filter, based on an Extended Kalman Filter for local measurements, and on Covariance Intersection for the fusion between local state estimates and estimates communicated by other spacecraft, eliminating EKF divergence problems. For Guidance and Control, an algebraic closed-loop algorithm, based on Pontryagin's maximum principle, is proposed, minimizing the propellant consumption and ensuring collision avoidance. Simulation results for a GTO 3-spacecraft formation are presented.

08:50 **AAS 06 - 159** **LQR Control Schemes to Satisfy the Separation Distance Constraints on the NASA Benchmark Tetrahedron Constellations**
Pedro A. Capo-Lugo, Peter M. Bainum, Howard University

The proposed tetrahedron constellation requires that the separation distance constraints must be maintained at every apogee point. Previously, the authors developed a strategy based on the orbital elements to maintain the constellation for a limited number of complete orbits. A control strategy is needed to satisfy the separation distance constraints at subsequent apogee points. This constellation is proposed to be in an elliptical orbit, and the linearized Tschauner-Hempel equations are used to explain the movement of a pair of satellites. Bainum, Strong, and Tan developed an LQR strategy based on these linearized equations, but a a similar LQR scheme will also be determined following the control strategy defined by Carter and Humi; in this way, both control schmes are compared to determine the best response.

09:15 **AAS 06 - 160** **Robust Stationkeeping Control for Libration Point Orbits**
Yunjun Xu, University of Oklahoma

Libration orbit stationkeeping controls have been designed based on reference orbit trajectories. The baseline trajectory is designed to meet science requirements and in the same time achieve the minimum fuel consumption. The successful of the librationpoint reference orbit is based on accurate numerical computation, and knowledge of the dynamics and space environment. The linear quadratic regulator controller has been developed widely for maintaining a spacecraft in a libration orbit reference trajectory as close as possible. However, any dynamics models including the restricted three body problem, space environment, sensor, and actuator, are only approximations of real physical systems.

09:40 Break

10:00 AAS 06 - 161 Formation Design and Geometry for Keplerian Elliptic Orbits with Arbitrary Eccentricity

Prasenjit Sengupta, Srinivas R. Vadali, Texas A&M University

The well-known Hill-Clohessy-Wiltshire equations that are used for formation flight design, have, until now, lead to designs that assume a circular reference orbit. Popular solutions like the projected circular orbit requirement no longer hold in the presence of eccentricity. A parameterization is developed for relative motion in a linearized field about a Keplerian orbit of arbitrary eccentricity. Eccentricity-induced effects are studied and exploited to obtain desired shapes of the relative orbit. Thesesolutions result in lower formation-keeping costs than the traditional Hill's solutions, because they accurately represent effects of eccentricity on formation dynamics, while maintaining much of the desired geometry.

10:25 AAS 06 - 162 Periodic Relative Motion Near a Keplerian Elliptic Orbit with Nonlinear Differential Gravity

Prasenjit Sengupta and Srinivas R. Vadali, Texas A&M University

A perturbation approach for determining relative motion equations and initial conditions for periodic motion in the vicinity of a Keplerian orbit with arbitrary eccentricity is presented. The initial conditions are obtained in the phase space of the rotating coordinate system, centered at the reference satellite. The analysis accounts for second-order terms in the expansion of the differential gravitational acceleration. Relative orbits generated using the methodology of this paper remain bounded over very long periods. The results are general and are applicable for arbitrary epoch. These results can serve as excellent guesses for initiating a numerical procedure for matching the semimajor axes of a formation.

10:50 AAS 06 - 163 Numerical Searches of J2 Invariant Orbits

Hui Yan, Kyle T. Alfriend, Texas A&M University

In this paper we investigate numerical searches of J2 invariant orbits. For passive J2 invariant orbits we use linear and nonlinear searches to find the optimal differential elements which minimize the secular drifts. This result agrees with the solutionfrom the periodic matching conditions. The full paper will include active J2 invariant orbits or maintenance of J2 invariant orbits.

11:15 AAS 06 - 164 Fuel Optimal of Spiral Maneuvers for Deep Space Multi-Spacecraft Interferometric Imaging Systems.

Jaime L Ramirez, Suman Chakravorty, Texas A&M University

We studied the design of minimum fuel maneuvers for multi-spacecraft interferometric imaging systems. It was shown that the underlying optimization problem is computationally intractable, by mapping it into a Generalized Traveling Salesman Problem, and thus it is necessary to resort to heuristics. We reduce the solution space to the subspace of spiral orbits, and as an application of the methodology developed we find fuel optimal spiral maneuvers for a deep space imaging application and calculate the fuel consumption, fuel to dry mass ratio and power requirements of these systems in order to gain knowledge about the feasibility of these systems.

Jan 24, 2006

Session 10: Orbit Mechanics II

Chair: David Vallado
AGI

13:30 **AAS 06 - 165** **Hamilton's Principal Function for the Two-Body Problem**
Oier Penagaricano Munoa, Daniel J. Scheeres, University of Michigan

Hamilton's principal function for the two-body problem is presented. Using Hamilton's principle and the velocity to go in the targeting problem, we are able to show that the proposed function describes the motion in the two-body problem. This allows us toautomatically solve the two-point boundary value problem. With the proposed function we are also able to derive Lambert's equation form a completely different perspective.

13:55 **AAS 06 - 166** **Autonomous Regulation of Spacecraft Motion About Unstable Periodic Orbits Using Impulsive Maneuvers**
Hiroaki Fukuzawa, University of Michigan

This paper presents a control method for autonomous regulation of spacecraft motion about unstable periodic orbits by occasional impulsive maneuvers. The impulsive maneuver to be applied at each prescribed time is obtained by modulating the difference between the actual state and the reference state of the motion at the time. The presented method is based on that of Generalized Sampled-data Hold Function (GSHF) control which is known to be useful in stabilizing motion about unstable periodic orbits. Themaneuver rule is obtained so that the impulsive maneuvers mimic the efficacy of GSHF control. The method is applied to a halo orbit spacecraft in a general planet-satellite system as an illustration.

14:20 **AAS 06 - 167** **Analysis of the Guidance Error Incurred by Various Autonomous Satellite Rendezvous Maneuvers**
Denise L. Brown, Penn State University; Thomas Lovell, AFRL; Mark Tollefson, Dynacs Military and Defense

In previous work, multiple-impulse maneuver algorithms for relative motion trajectory reconfiguration have been developed based on the Clohessy-Wiltshire-Hill’s equations. Such schemes are useful in the case of relative motion missions such as formationflying and rendezvous. They are, however, inaccurate due to being derived based on the simplistic Hill’s assumptions. In this paper two alternate methods are used to compute the maneuvers; one based on a higher-fidelity relative motion model than Hill’sand the other based on absolute (Keplerian) motion. The relative agreement between the various schemes is then explored, and all trajectories are compared to a “truth” trajectory.

14:45 **AAS 06 - 168** **On the design of a science orbit about Europa**
Martin Lara, Real Observatorio de la Armada, Spain; Ryan Russell, Jet Propulsion Laboratory

A science mission about Europa requires high-inclination low-altitude orbits. However, perturbations of Jupiter on the orbiter result in instability. Previous approaches to maximize the lifetime of the orbiter use the double averaged problem. We work withthe non averaged equations and find unstable periodic orbits with long lifetimes. Further, our solutions repeat the trace on the surface of Europa after long cycles, making them suitable for mapping missions.

15:10 **Break**

15:30 **AAS 06 - 169** **Periodic Orbits in the Full Two-Body Problem**
J. Bellerose & D.J. Scheeres, University of Michigan

The dynamics of a binary system are studied. We solve for periodic orbits using a Poincar´e map reduction method. We first look at the general case of the "sphere restriction" where one of the bodies is modeled as a sphere. Using conservation of energy and angular momentum, periodic orbits can be investigated for values of the distance between the primaries, angular velocity and body size parameters. We specialize the method for a ellipsoid-sphere system where the second body is modeled as a constant density tri-axial ellipsoid. Using numerical simulations we show regions of existence and stability of periodic orbits.

15:55 **AAS 06 - 170** **Practical Challenges in Implementing Atmospheric Density Corrections to the NRLMSISE-00 Model**
Matthew P. Wilkins, Chris Sabol, Air Force Maui Optical and Supercomputing Center; Paul J. Cefola, Consultant and Reasearch Affiliate at MIT; K. T. Alfriend, Texas A&M University

The goal of this effort is to apply atmospheric density corrections to the NRLMSISE-00 model to provide a significantly more accurate orbit prediction and determination capability. In order to effectively use these density corrections, the underlying atmospheric model must be used in a manner consistent with the way the corrections were generated. This paper will describe the implementation of the NRLMSISE-00 atmospheric model into GTDS and the steps required to ensure commensuration with the atmosphericdensity corrections generated by Dr. Vasiliy Yurasov. Recommendations are made concerning the computation of various input parameters to the NRLMSISE-00 model.

16:20 **AAS 06 - 171** **Unmanned Orbiter Undocking: Method for Disposal of a Damaged Space Shuttle Orbiter**
Ray Bigonesse, William R. Summa, United Space Alliance, Houston

In the aftermath of the Columbia accident in 2003, NASA launched an effort to determine how to use the International Space Station (ISS) as an orbiting "safe haven" for Space Shuttle crews in the event that an Orbiter is irrepairably damaged during ascent. Rather than risk the safety of a Shuttle crew, they would take refuge on the ISS while a rescue flight is launched to return them to Earth. To free the sole ISS Orbiter docking port for this purpose, NASA had to develop new techniques to perform the seemingly impossible task of undocking an unmanned Orbiter from the ISS, and then remotely piloting it through a safe separation and deorbit burn. Several key obstacles had to be overcome to accomplish this goal.

16:45 **AAS 06 - 172** **Revisiting Spacetrack Report #3**
David A Vallado, Analytical Graphics Inc., Center for Space Standards and Innovation

Over a quarter century ago, the US government (USG) released the equations and source code used to predict satellite positions (Hoots et al., 1980, commonly called SpaceTrack Report Number 3). In the 1990s, code changes were made to handle rare cases encountered in operations, but unfortunately these changes were never publicly released. Thus, the USG code used today to produce TLEs and the code most users use do not match, introducing unnecessary errors. Independent efforts, technical papers, and source code over the past decade decade enable us to produce a publicly available version which corrects these deficiencies. This paper provides source code, test cases, results, and analysis of a version of SGP4 designed to be similar to the operational Air Force Space Command code.

Jan 24, 2006

Session 11: Deep Impact Special Session

Chair: L. Alberto Cangahuala
Jet Propulsion Laboratory

13:30 **AAS 06 - 173** **An Overview of Deep Impact Navigation with Lessons Learned**
Raymond B. Fraiuenholz, Jet Propulsion Laboratory

Deep Impact met its' primary objective on July 4, 2005 when a smart Impactor guided itself into the path of comet 9P/Tempel 1. The mother Flyby spacecraft then observed and recorded the collision and subsequent plume development. Ground-based navigatorsprovided optical navigation, maneuver design and evaluation, plus orbit determination using both radio and optical data. The unprecedented navigation performance established a new standard for comet missions, but there were several important lessons learned along the way. This paper summarizes key navigation strategies and results, and identifies several lessons learned that can aid future navigators challenged by similar mission objectives.

13:55 **AAS 06 - 174** **Ground-based Orbit Determination for Deep Impact**
Mark Ryne, David Jefferson, Diane Craig, Earl Higa, George Lewis, Prem Menon, Jet Propulsion Laboratory

The objectives of the Deep Impact project were to collide a smart "Impactor" spacecraft into comet Tempel 1 and observe the subsequent explosion, ejecta, and crater formation from a "Flyby" spacecraft. To achieve these goals, it was necessary for ground-based navigation to meet stringent requirements at Impactor release, 24 hours prior to the collision. This paper will discuss the details of the effort, which involved combining radiometric, interferometric, and optical navigation data to determine the trajectories of the spacecraft and comet Tempel 1. These estimates were successfully employed to design maneuvers and "seed" the autonomous navigation process on the Impactor spacecraft.

14:20 **AAS 06 - 175** **Deep Impact Ground Navigation Maneuver Design and Performance**
Ramachandra S. Bhat, Jet Propulsion Laboratory

Deep Impact consisting of an Impactor and a Flyby successfully accomplished its objective on July 4, 2005 when the Impactor collided with 9P/Tempel-1. The Flyby transmitted hundreds of pictures of the comet ejecta during and after the collision. The objective of the ground navigation maneuver strategy was to release the Impactor within 30km of the estimated comet center and to retarget the Flyby to a 500 km Tempel-1 flyby altitude with a delay in comet approach by 850 sec relative to the actual impact.To accomplish these objectives, required a maneuver sequence designed to account for several geometric constraints that restricted the allowable thrusting attitudes.

14:45 **AAS 06 - 176** **Optical Navigation for Deep Impact**
William M. Owen, Jr., Nickolaos Mastrodemos, Brian P. Rush, Tseng-Chang M. Wang, Stephen D. Gillam, Shyam Bhaskaran, Jet Propulsion Laboratory

Successful navigation of both the Impactor and Flyby spacecraft of the Deep Impact mission to comet 9P/Tempel 1 depended critically on the quality and timeliness of ground optical navigation data processing. Pictures of the comet, taken by the Flyby spacecraft, provided the most precise information on two dimensions of the comet-relative position of the Flyby. This paper describes the prelaunch analysis (including the picture schedule), the centerfinding tools, and the opnav results which figured so prominently in the success of the mission.

15:10 **Break**

15:30 **AAS 06 - 177** **Autonomous Navigation for Deep Impact**
Nickolaos Mastrodemos, Jet Propulsion Laboratory

The Deep Impact encounter with comet Tempel 1 was successfully completed on July 4 2005. The key mission goals was a collision of the Impactor spacecraft with the comet nucleus on an illuminated part of its surface, visible from the Flyby spacecraft thatoffers optimal viewing conditions to the Flyby's instruments and successful identification & tracking of the crater from the Flyby spacecraft for 800 seconds following impact. The encounter relied on the use of Autonomous Navigation (Autonav) software inorder to estimate each spacecraft's trajectory relative to the nucleus and a closed-loop interaction with the ADCS subsystem for nucleus tracking and maneuver execution.

15:55 **AAS 06 - 178** **Comet 9P/Tempel 1 Ephemeris Development for the Deep Impact Mission**
Steven R. Chesley, Donald K. Yeomans, Jet Propulsion Laboratory

The success of NASA's Deep Impact mission relied in part on an accurate ephemeris for the mission's target body, Comet 9P/Tempel 1. The orbit determination and prediction process is substantially more challenging for comets than for asteroids because of cometary outgassing, which leads to poorly modeled and quasi-random nongravitational accelerations, and because of known but uncharacterized systematic errors that plague the observational data. Even so, in the final analysis, the Tempel 1 ephemeris accuracy was more than sufficient to support the Deep Impact mission, and the delivered ephemeris uncertainties were substantially validated. In this paper, we discuss the challenges, successes and lessons learned in the course of this effort.

Jan 24, 2006

Session 12: Mission Analysis II

Chair: Dr. Thomas Starchville
The Aerospace Corporation

13:30 **AAS 06 - 179** **Multi-Body Orbit Architectures for Lunar South Pole Coverage**
D.J. Grebow, M.T. Ozimek, K.C. Howell, Purdue University; D.C. Folta, NASA Goddard Space Flight Center

A potential facility at the lunar south pole has prompted studies of orbit architectures to ensure adequate coverage. Constant communication can be achieved with two spacecraft in different combinations of Earth-Moon libration point orbits. Halo and vertical families, as well as other orbits near L1 and L2 are investigated. The investigation includes detailed results using eight different orbits with periods ranging from 7 to 16 days. Natural solutions are generated in a full ephemeris model, includingsolar perturbations. Using invariant manifold theory, a preliminary station-keeping analysis is also completed.

13:55 **AAS 06 - 180** **Computing Low-Thrust Orbit-Raising and Lunar Transfers**
Craig Kluever, University of Missouri-Columbia

Optimizing low-thrust transfers is a challenging problem, and obtaining optimal transfers is sometimes tedious and time consuming. In many cases, mission and spacecraft system analysts need to perform first-order preliminary trade studies where it is important to determine general trends among electric propulsion system parameters. In this paper, we demonstrate a new low-thrust trajectory tool that can compute orbit transfers for Earth-orbit raising missions and lunar missions. This tool can quickly and efficiently compute low-thrust transfers, and the results show a good match with fully optimized trajectories.

14:20 **AAS 06 - 181** **Study of Subcycles for Frozen Repeat Orbits, Application to the ICESAT and CRYOSAT Missions**
Nadège Pie, University of Texas at Austin

Frozen repeat orbits are often used in Earth and climate observation missions. Their dynamics and behavior have been investigated extensively. However, the dynamics of their subcycles are not so well-understood. This paper provides a first tool to analyzemore in detail the repeat frozen orbit subcycles. First, the evolutions of ICESat and CryoSat ascending nodes over their entire cycles were simulated. The data generated were later scanned to extract the ascending nodes corresponding to the subcycles. The results of the analysis are presented on graphs that are useful tools to decompose the frozen repeat orbits in sequences of subcycles.

14:45 **AAS 06 - 182** **Intermediate Rendezvous: A Mars Sample Return Strategy**
Chad Smith, Jet Propulsion Laboratory

This paper describes the issues and challenges related to the design of the rendezvous between the Earth return vehicle (ERV) and the orbiting sample (OS) for the Mars Sample Return (MSR) mission. In particular, attention will be focused on the strategyfor “optimizing” the intermediate segment of the rendezvous process, during which there are a great number of variables that must be considered and well understood.

15:10 **Break**

15:30 AAS 06 - 183 Guidance and Navigation Operation for Rehearsals and Touch-downs

Jun'ichiro Kawaguchi, The Institute of Space and Astronautical Science (ISAS) / JAXA

Hayabusa performed five descents, among which two touch-down flights were included. Actually Hayabusa made three touching-downs and one long landing on the surface during those two flights. This paper summarizes how a series of descent were planned and operated. The contents focus their attention on correction maneuvers planning, What kind of terminals with what kind of software tools were actually built and used. The project team had distilled and accumulated their experiences through the flights and accomplished the mission. This paper presents the story about it, too.

15:55 AAS 06 - 184 Optimal Eccentricity Vector for Geosynchronous Satellite Disposal

Glenn E. Peterson, The Aerospace Corporation

The successful disposal of geosynchronous (GEO) satellites is increasing in importance as the GEO belt becomes more populated. Studies have found that by targeting the eccentricity vector to point at the Sun, the 100-year perigee altitude time history ofa disposed GEO satellite stays consistently higher above GEO than it otherwise would by up to 40-50 km. However, an additional improvement can be had if an optimal eccentricity vector is targeted that is close to, but not directly at, the sun-pointing direction. Following the optimal vector can increase the clearance by an additional 5-15 km.

Jan 25, 2006

Session 13: JIMO Special Session

Chair: Jon Sims
Jet Propulsion Laboratory

08:00 **AAS 06 - 185** **Jupiter Icy Moons Orbiter Mission Design Overview**
Jon A. Sims, Jet Propulsion Laboratory

An overview of the design of a mission to three large moons of Jupiter (Callisto, Ganymede, and Europa) is presented. The Jupiter Icy Moons Orbiter (JIMO) mission uses ion thrusters powered by a nuclear reactor to transfer from Earth to Jupiter and entera low-altitude science orbit around each of the moons. The combination of very limited control authority and significant multibody dynamics resulted in some aspects of the trajectory design being different than for any previous mission. The results ofseveral key trades, innovative trajectory types and design processes, and remaining issues are presented.

08:25 **AAS 06 - 186** **The Jupiter Icy Moons Orbiter Reference Trajectory**
Gregory J. Whiffen, Try Lam, Julie A. Kangas, Jet Propulsion Laboratory

The proposed NASA Jupiter Icy Moons Orbiter (JIMO) mission would use a single spacecraft to orbit Callisto, Ganymede, and Europa in succession. The enormous Delta-Velocity required for this mission (nearly 25 [km/s]) would necessitate the use of veryhigh efficiency electric propulsion. The trajectory created for the proposed baseline JIMO mission may be the most complex trajectory ever designed. This paper describes the current reference trajectory in detail and describes the processes that were used to construct it.

08:50 **AAS 06 - 187** **Jupiter Icy Moons Orbiter Interplanetary Injection Period Analysis**
Theresa D. Kowalkowski, , Julie A. Kangas, Daniel W. Parcher, Jet Propulsion Laboratory

This paper investigates the sensitivity of the planned Jupiter Icy Moons Orbiter mission to variations in interplanetary injection date, magnitude, and direction, starting in a low-Earth assembly orbit. These results are used to determine the frequency and number of injection opportunities from a precessing assembly orbit. It is shown that the use of a low-thrust propulsion system with a nuclear-electric power source would allow the interplanetary trajectory performance to be relatively insensitive to variations in injection conditions. This result yields many injection opportunities due to the long injection period and consecutive orbits with favorable geometry.

09:15 **AAS 06 - 188** **Characteristics of Transfers to and Captures at Europa**
Try Lam, Julie A. Kangas, Jet Propulsion Laboratory; Anil N. Hirani, University of Illinois

This paper explores the characteristics (i.e. stability and performance) of transfers to, and captures at Europa. We focus on optimal low-thrust transfers from Ganymede to potential science orbits at Europa and compare different capture types, transfer resonances, and thrust accelerations. The two types of capture methods we consider are capture in a distant retrograde orbit (DRO) and capture by targeting a state on a stable invariant manifold of a halo orbit. We show that each type has its advantages anddisadvantages. The first part of DRO-type capture may be easier than a halo-type capture in some design schemes because DROs are generally extremely stable. However changing the inclination to achieve a high inclination science orbit at Europa is much easier in a halo-type capture.

09:40 **Break**

10:00 AAS 06 - 189 Designing Capture Trajectories to Unstable Periodic Orbits Around Europa
Ryan P. Russell, Try Lam, Jet Propulsion Laboratory

The stable manifolds of unstable periodic orbits in the Restricted Three Body Problem are utilized to attract a spacecraft towards Europa. By selecting an appropriate periodic orbit from a large pre-existing database, a mission designer can control important characteristics of the captured orbit including altitudes, inclinations, and radii. Several free-parameters are optimized in the non-trivial mapping to a realistic model. Although the ephemeris capture orbit is ballistic by design, low-thrust is used to target the capture orbit and control the spacecraft after arriving on the unstable quasi-periodic orbit. The method provides structure and controllability to the capture trajectory that otherwise

10:25 AAS 06 - 190 The Role of Invariant Manifolds in Low Thrust Trajectory Design (Part III)
Martin Lo, Jet Propulsion Laboratory

This paper is the third in a series to explore the role of invariant manifolds in the design of low thrust trajectories. In previous papers, we analyzed an impulsive thrust resonant gravity assist flyby trajectory to capture into Europa orbit using the invariant manifolds of unstable resonant periodic orbits and libration orbits. The energy savings provided by the gravity assist may be interpreted dynamically as the result of a finite number of intersecting invariant manifolds. In this paper we demonstrate that the same dynamics is at work for low thrust trajectories with resonant flybys and low energy capture. However, in this case, the flybys and capture are effected by continuous families of intersecting invariant manifolds.

10:50 AAS 06 - 191 A Toolbox For Designing Long-Lifetime Orbits About Planetary Satellites: Application to JIMO at Europa
Marci E. Paskowitz, Daniel J. Scheeres, University of Michigan

In this paper, we describe a toolbox used to design long-lifetime orbits about planetary satellites. In particular, to satisfy the science requirements of missions to planetary satellites, these orbits have low-altitudes and are near-polar. The toolbox can be used to obtain a description of the underlying dynamics of the system under consideration, to compute the initial conditions that will yield long-lifetime orbits and to numerically integrate a set of initial conditions. We use this toolbox to designorbits for the Jupiter Icy Moons Orbiter mission at Europa.

11:15 AAS 06 - 192 Orbit Determination Studies for a Low-Altitude Europa Orbiter
Paul F. Thompson, Sumita Nandi, and Mau C. Wong, Jet Propulsion Laboratory

Orbit simulations were conducted for a 30-day Europa mission with a 100-km, near-polar orbit. The reconstructed orbit accuracy was 50 m, 60 m, 30 m (3-sigma) for the radial, crosstrack, and alongtrack components respectively and was dominated by the relatively large level of a priori gravity error, with secondary effects due to maneuver execution errors. Orbit error predictability in the presence of no tracking data was dominated by 1-rev perturbations for the crosstrack and radial components while thealongtrack error exhibited a nearly secular increase in the absence of tracking data at a rate of ~5 m/day (3-sigma).

Jan 25, 2006

Session 14: Optimization II

Chair: Ron Proulx
Draper Laboratory

08:00 **AAS 06 - 193** **A Suborbital Spaceship for Short Space Duration and Microsat Launch**
Yunjun Xu,Jangho Yoon, University of Oklahoma; Pat Bahn, TGV Rockets Inc., Norman OK

Suborbital reusable launch vehicles have become a hot topic for recent years. This paper discusses launch capabilities of one of such vehicles, which is a small vertical takeoff vertical landing suborbital rocketship. This provides unique and interesting capabilities for payload test and qualification, development and short duration experimentation. Theoretical possibilities include micro-sat launch and payload delivery. Here, trajectory design and application will be discussed in detail. Basically, (1) the first stage of the vertical takeoff vertical landing suborbital rocket can provide 200 seconds combined vacuum, micro-gravity and thermal environments. With a second stage, (2) this rocket can provide a possibility for a low earth orbit microsat insertion and (3) deliver a 150 kg upper stage payload over 3200 km or achieving a 1800-second flight time.

08:25 **AAS 06 - 194** **Autonomous Rendezvous Guidance and Navigation for Orbital Express and Beyond**
Joe Evans, Elfego Pinon III, Tom Mulder, The Boeing Company, Houston, Texas

This paper examines design and application of autonomous rendezvous guidance and navigation flight software for an unmanned spacecraft from a range of 200 km to capture of a non-cooperative spacecraft. The onboard code processes data from multiple sensors and executes nominal and contingency trajectories planned by the flight design team. The guidance system sequences through translation and pointing modes during rendezvous, proximity operations, and capture of the target vehicle. To satisfy requirements for autonomous operation, the software reacts to critical failures by directing the spacecraft to a fuel-efficient stationkeep location, while awaiting further instruction from the ground.

08:50 **AAS 06 - 195** **Development of a Simple Analytic Model for Optimum Specific Impulse Interplanetary Low Thrust Trajectories**
David Oh, Jet Propulsion Laboratory

Progress is reported towards a simple analytic model for interplanetary nuclear electric low thrust trajectories. The objective is to develop an analytic performance model that will explain trends observed in optimized specific impulse circular-coplanar low thrust transfers, identify governing variables and fundamental relationships, and efficiently calculate system parameters (mass and flight time). The model calculates system performance parameters using a combination of simple empirical and physics based relationships. A full analytic model has been developed for Earth-Jupiter transits and partial models have been developed for transits from Earth to Saturn, Neptune, and Kuiper belt objects.

09:15 **AAS 06 - 196** **Multi-Objective Parallel Genetic Algorithms Applied to the Primer Vector Control Law**
Seungwon Lee and Ryan P Russell, Jet Propulsion Laboratory

A global, Pareto, and parallel optimization method for low-thrust orbit transfers is developed by applying a multi-objective parallel genetic algorithm to the Primer Vector control law. The Primer Vector control law generates a thrust profile for given initial co-states. Then the genetic algorithm finds the initial co-states that both satisfies the target state's boundary condition and minimizes Delta_V and flight time. The method yields Pareto-optimal solutions, which demonstrate the trade-off between Delta_V and flight time. The present method is applied to two problems: 1) two-body orbit transfer around the Earth, and 2) restricted three-body distant retrograde orbit transfer around Europa.

09:40 **Break**

10:00 **AAS 06 - 197** **Optimal Space Trajectory Design: A Heuristic-Based Approach**
Christopher R. Bessette, David B. Spencer, The Pennsylvania State University

Using Lambert's Algorithm, orbital trajectories that require low delta v's and small flight times are found using Evolutionary Algorithms (EA). Three different heuristics were used in the analysis of this problem: Particle Swarm Optimization (PSO), Differential Evolution (DE), and Covariance Matrix Adapted Evolutionary Strategies (CMA-ES). In the two transfers examined the EA found solutions which were marginally more expensive in delta v, and with a much lower rendezvous time. The CMA-ES had the quickest convergence but poor reliability. PSO took slightly more time, but with a perfect reliability record, it was deemed the best algorithm to solve this problem.

10:25 **AAS 06 - 198** **Optimal Trajectory Design for Multiple Asteroid Impact and Sample Return Missions**
Massimiliano Vasile, University of Glasgow

In this paper some transfer options for missions to Near Earth Objects have been studied. Due to the high number of potential targets ad to the large variety of possible missions that can be considered, an extensive analysis of different transfer optionswould require an efficient optimization approach. Here low-thrust transfers have been modeled through a novel shape-based approach and a global optimization method has been used to look for globally optimal transfers. Different targets have been identified and various mission scenarios have been considered: rendezvous, sample return and impact missions, all of them with or without gravity assist maneuvers.

10:50 **AAS 06 - 199** **Optimizing Trajectories for Suborbital Human Spaceflight**
Ryan L. Kobrick, David B. Spencer, The Pennsylvania State University

The ANSARI X PRIZE has been won and the future objective for private spaceflight has expanded to reaching space as many times as possible during a fiscal year. The goals of this paper are to show how trajectories can be customized to meet the demands ofthe paying passenger by the manipulation of vehicle performance variables, and to develop a "menu" of possible flight options based on user defined interests. A parametric trade off study to find the best flight for a given set of criteria was performed,and a menu of possible flight options has been developed.

11:15 **AAS 06 - 200** **The Computation of Optimal Rendezvous Trajectories using the Sequential Gradient Restoration Algorithm**
Michael W. Weeks, Dr Angelo Miele, Rice University

A rendezvous trajectory is defined by its ability to control the relative motion between two spacecraft. Likewise, the optimal solution of a rendezvous problem consists of finding an allowable control distribution u(t)which minimizes some prescribed performance index (i.e. time, fuel, etc) and brings the maneuvering vehicle into coincidence with the target, while simultaneously satisfying certain operational & physical constraints. This paper derives the general equations of motion for the rendezvous problem, and demonstrates the successful implementation of the Sequential Gradient Restoration Algorithm (SGRA) to optimize several rendezvous trajectories for both the case of a target vehicle in an initial circular and an initial elliptic orbit, and assuming finite duration burns.

Jan 25, 2006

Session 15: Formation Flying III

Chair: Dr. Kathleen Howell
Purdue University

08:00 **AAS 06 - 201** **A Comparison of Impulsive Hovering Satellite Trajectory Design Methods with Emphasis on Relative Orbit Elements**

T. Alan Lovell, Air Force Research Laboratory; Denise L. Brown, Penn State University; MarkTollefson, Dynacs Military and Defense

This paper details the design of a trajectory that puts a satellite into a quasi-hovering pattern relative to a reference satellite. Several authors have investigated this "teardrop" trajectory in the past, however the derivations of their expressions for the geometry of the trajectory shape have been rather complex. The current paper analyzes the impulsive hovering concept using an approach not tried by previous authors. This involves relative orbit elements, which give more of a geometric than a Cartesian description of the satellite's relative motion. These allow for much simpler derivations of the same expressions, with no loss of generality.

08:25 **AAS 06 - 202** **Dual-Compatible Flower Constellations**

Daniele Mortari, Texas A&M University; Matthew Paul Wilkins, Naval Postgraduate School

This paper summarizes important properties of the Flower Constellations and introduces the theory of Dual-Compatible Flower Constellations. Flower Constellation's Phasing and Secondary Paths are firstly discussed, then the relationships establishing the equivalency of two Flower Constellations, are provided. The Flower Constellation phasing scheme adopted here, uses an additional parameter, the phasing step Fh, that further enlarges the dimensionality of the potential solutions. Then it is shown how to simplify the design parameters by introducing an equivalent ``contiguous'' satellite distribution. Finally, the theory of Dual-Compatible Flower Constellation is introduced and some examples are given.

08:50 **AAS 06 - 203** **Flower Constellations Design Using Evolutionary Algorithms**

Christian Bruccoleri, Texas A&M University

A number of existing satellite constellation concepts focus only on a particular kind of constellation, e.g. Walker constellations. The recently introduced Flower Constellations instead constitute an infinite set of constellations characterized by periodic dynamics whose corresponding trajectories in the Earth-Centered Earth-Fixed frame constitute a continuous, closed-loop, symmetric pattern. Flower Constellations can be exploited to greatly extend the design possibilities, but relating the shape of theconstellation to the choice of the design parameters has proven very hard. Therefore, using Evolutionary Algorithms to find the design parameters that generate the desired configuration seems to be a promising route.

09:15 **AAS 06 - 204** **Uni-Flower: A Novel Proposal for University-Built Nanosatellites in Flower Constellations**

Troy Henderson, Daniele Mortari, Helen Reed, Texas A&M University

The basic outline for a novel research project is proposed which makes use of micro- or nanosatellites-built solely by universities-in a FC orbit determined by the mission of the satellites. Two specific scenarios are descried in detail, with options left open for input, feedback, and completely new mission ideas. The projects detailed are: 1) a FC orbiting the Earth for magnetic field dynamic measurement and correlation with solar events and 2) an active/passive Earth atmospheric observation mission.Recent progress will be given for using FCs for continuous regional coverage. For the detailed missions, the orbit design, satellite design, educational possibilities, and university interaction and collaboration prospects (as well as multi-disciplinaryaspects) are thoroughly discussed.

09:40 **Break**

10:00 **AAS 06 - 205** **Online Relative Range Determination and Clock Synchronization Algorithm for Formation Flying Spacecraft**

Yuichi Tsuda, Tomoaki Toda, Yoshifumi Saito, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency

JAXA is currently planning the next generation magnetosphere observation mission called ?SCOPE? (cross-Scale Coupling in Plasma universE). SCOPE aims at observing the Earth's magnetotail with 5 satellites flying in formation to fully resolve the temporaryand spatial distribution of the magnetospheric phenomena. For this observation, the clock synchronization and relative distance measurement between the spacecrafts are essential. This paper describes an onboard relative ranging and clock synchronizationalgorithm, which applies an approximated Kalman filter, using the time tags of the sent/received signals as the filter inputs to suit to the intersatellite ranging and clock synchronization system considered for SCOPE mission.

10:25 **AAS 06 - 206** **Periodic relative motion of formation flying satellites**

Marco Sabatini, Riccardo Bevilacqua, Mauro Pantaleoni, University of Rome; Dario Izzo, ESA-ESTEC Advanced Concept Team, Noordwijk

A periodic solution for relative motion can be of great value for a number of missions involving satellites in formation. This work shows that, if the J2 perturbation is considered, periodic relative orbits are possible only in correspondence of zero secular drift of perigee of the reference orbits, i.e. at critical inclinations of i=63.434° and i=116.565°. However, other sets of orbital parameters minimize the J2 disturb and admit nearly periodic relative motion. For LEO, an inclination of 50° grants this possibility.

10:50 **AAS 06 - 207** **Optimal Deployment of Spacecraft Formation at Sun-Earth L2 Point**

Gianmarco Radice, University of Glasgow

During formation deployment, re-sizing and re-orientation, the spacecraft must reach their desired positions without incurring in collisions or somehow interfering with each other. The degree of flexibility and the accuracy in the relative position and attitude required is difficult to achieve using conventional GNC algorithms. The potential function method, based on Lyapunov's second theorem on stability, brings the advantage of robustness and flexibility, along with light computational workload on the control system. The aim of this paper is to improve the performance of existing algorithms based on this method. In particular, the focus is on reducing the fuel consumption.

11:15 **AAS 06 - 208** **Novel Configuration, Orbit Design and Baseline Performance Analysis of Interferometric SAR Formations**

Zhang Jinxiu, Cao Xibin, Lin Xiaohui, Research Center of Satellite Technology, Harbin Institute of Technology, P.R.C.

Taken into account J2 perturbation, novel formation configuration of three satellites is presented. According to different requirements for DEM and GMTI of single pass interferometric SAR, the space baselines are respectively achieved and considered as maximum separation of radial/out-of-plane and in-track. Each satellite initial phase angles are followed from formation configuration. The mean elements differences between chief and each deputy satellite are preliminary determined. In order to maintain thestable space baselines in J2 perturbation, the mean semi-major axises differences are little modified. The initial mean elements are transformed into osculating elements. The interferometric SAR formation is established.

Jan 25, 2006

Session 16: Hayabusa and NEO Missions

Chair: Dr. James Gearhart
Lockheed Martin Technical Operations Co.

13:30 **AAS 06 - 209** **Optical Hybrid Navigation in Hayabusa - Approach, Station Keeping & Hovering**
Jun'ichiro Kawaguchi, Tatsuaki Hashimoto, Japan Aerospace Exploration Agency; Takashi Kominato, Masashi UO, Ken'ichi Shirakawa, NEC Aerspace Systems Co.

Hayabusa (MUSES-C) performed an approach to rendezvous with its target asteroid Itokawa and has performed a proximity operation including station keeping and hovering around Itokawa. In order to navigate and to guide the spacecraft to Itokawa, it made highly use of optical hybrid navigation technique combined with the radio-metric information obtained on the ground. Hayabusa is equipped with a sophisticated autonomous navigation and guidance function including onboard image processing and the like. This paper reports how those autonomous capability has been utilized in the actual flight operation, at the same time showing the flight results.

13:55 **AAS 06 - 210** **Ion Engines Cruise of Hayabusa to Itokawa - Trajectory Synthesis and Results**
Jun'ichiro Kawaguchi, ISAS, Japan Aerospace Agency; Masatoshi Matsuoka, Takashi Kominato, NEC Aerospace Systems Corporation

Hayabusa (MUSES-C) spacecraft made two and four month voyage propelled via ion engines combining the earth gravity assist, and arrived its target near earth asteroid Itokawa on September 12th, 2005. At both the earth swingby and the arrival at Itokawa, most velocity correction was performed by the ion engines and the flight was very successful. It utilized a new technique combining both low thrust with gravity assist to garner amplification energy surplus. This paper presents how the ion engines cruise trajectory had been synthesized through having incorporated practical constraints imposed to the spacecraft attitude, power and so on.

14:20 **AAS 06 - 211** **Asteroid 4660 Nereus Sample Return Mission**
Gianmarco Radice, University of Glasgow

In this paper the feasibility of a NEO sample return mission has been investigated. Asteroid 4660 Nereus, satisfying both scientific interest and mission feasibility requirements, was identified as a suitable target after detailed studies. A multiple shooting method enabled efficient optimisation of the objective function for several direct and complex heliocentric trajectories using both chemical and low-thrust propulsion systems. From launch to Earth re-entry, the total mission duration is 5 years and 2months, including a 5 months NEO stay time. The total system mass, comprising orbiter, lander and return module, and including a 30% mass margin, is 2000 kg.

14:45 **AAS 06 - 212** **Mission Analysis of Near Earth Asteroid Exploration by Miniature Asteroid Interceptors**
Yasuhiro Kawakatsu, Osamu Mori, Yuichi Tsuda, Jun'ichiro Kawaguchi, ISAS/JAXA; Kota Tarao, Univ. of Tokyo

Discussed in this paper is near Earth asteroid explorations by miniature Asteroid Interceptors. The Interceptor is an autonomous self-contained interplanetary probe with 10kg mass which is now under development in ISAS/JAXA. Firstly discussed is the single use of the Interceptor as a piggy back payload of the geostationary mission, which enables the minimum size interplanetary mission. The utilization of the Earth synchronous orbit drastically increases the number of the possible target asteroids. Next discussed is the multiple asteroids exploration with a single launch. An option to overcome the difficulty in performing critical operation of multiple spacecrafts simultaneously is also discussed.

15:10 **Break**

15:30 **AAS 06 - 213** **A Survey of Rendezvous and Impact Ballistic Trajectories to NEOs**
Carlos Corral van Damme, Raúl Cadenas, Mariella Graziano, GMV, Tres Cantos, Spain

A possible scenario for a preparation mission to deflect a Near Earth Object (NEO) would consist of two spacecraft: one will rendezvous with the target NEO, study it at close distance, and measure the deflection caused by the other spacecraft, that will impact the NEO at high relative velocity. This paper investigates both rendezvous and impact ballistic trajectories to NEOs, focusing on low cost missions. The trajectory options examined include direct transfers, single Venus and Mars swingbys, and Delta-V Earth and Venus gravity-assist manoeuvres. The results obtained show the feasibility of this type of mission concept based on ballistic trajectories.

15:55 **AAS 06 - 214** **Hayabusa's Touching-down to Itokawa - Autonomous Guidance and Navigation**
Jun'ichiro Kawaguchi, Takashi Kubota, Tatsuaki Hashimoto, JAXA; Masashi Uo, Ken'ichi Shirakawa, NEC Aerospace ; Shinji Hagino, Takeshi Ohshima, NEC-Toshiba Space

Hayabusa attempted to touch-down two times in November with one rehearsal descent. They were successfully performed. The autonomous guidance and navigation capability is installed aboard the spacecraft. It collects the laser altimeter, laser range finders and navigation cameras information aboard and is designed to estimate where the spacecraft is and to decide the path correction maneuvers by itself. The function programmed includes the image processing designed to detect an artificial target marker location, with which the spacecraft is designed to approach to it. This paper presents how this difficult and sophisticated events were carried out, showing flight results along.

16:20 **AAS 06 - 215** **Accurate Landmark Tracking for Navigating Hayabusa prior to Final Descent**
Masashi Uo, NEC Aerspace Systems Corporation, Japan

What Hayabusa demonstrated was, first of all, a pin-point landing whose size is just 20 to 30 meters in radius. This required an extraordinary accurate orbit estimation during the descent. Just one centimeter dispersion may have resulted in 36 meters inone hour. And the flight needed almost Worms' Speed control and management. What contributed to this was in the landmark tracking navigation. Conventional landmark tracking took a lot of time. But the Hayabusa project team developed a new tool that combines human's assist with the computer aided terrain display. A real-time landmark navigation did contribute to the
successful precise navigation to the specified area on the surface. This paper presents the essence of it.

16:45 **AAS 06 - 216** **Use of Laser Range Finders in Terrain Alignment and Touchdowns**
Takashi Kubota

Hayabusa spacecraft autonomously performed a Terrain Alignment maneuver that accomplished both altitude and attitude control whose reference was the surface itself. Hayabusa spacecraft was equipped with four beams Laser range Finder (LRF) aboard. It played a very important role to control its position and attitude at the very low altitude, when the spacecraft was out of remote control and was supposed to perform this task pure autonomously. Actually, Hayabusa spacecraft hovered with this method at 17 meters high at the first touching-down attempt and at 7 meters high at the second touching-down attempt. This paper presents how these autonomous control was performed in detail.

Jan 25, 2006

Session 17: Navigation

Chair: Frederic Pelletier
JPL

13:30 **AAS 06 - 217** **Outgassing Acceleration of a Spacecraft**
James K Miller, KinetX, Inc.; Connie J. Weeks, Loyola Marymount University

Outgassing from a spacecraft results in an acceleration of the spacecraft that may be computed from the kinetic theory of gases. The equations of motion for gas molecules confined within a container are shown to lead to a normal distribution of speed inany given direction as a result of collisions. This normal one dimensional distribution of speed may be mapped into the Maxwellian distribution for the magnitude of velocity. From the Maxwell probability distribution, the average energy and momentum ofthe gas molecules is developed and these are related to the thrust and specific impulse of the vented gas.

13:55 **AAS 06 - 218** **Planet and Time Estimation using Star Trackers**
Daniele Mortari, Texas A&M University

This paper presents an automatic approach to identify an observed visible planet (Venus, Mars, Jupiter, and Saturn) using star trackers and no time information. Moreover, once the planet is identified, then the proposed technique shows how to estimate thetime. The proposed technique to perform planet identification is extremely fast because the approach adopted to access a 2-Dimensional planet database is based on the k-vector technique. The planet identification algorithm never failed during extensive numerical tests. The accuracy of the estimated time is a function of the observed planet, of the particular geometry, and of the database size. For a relatively small planet database, and avoiding complicate situations (knots) the time estimation for the worst geometry and planet (Saturn) is always better than a day.

14:20 **AAS 06 - 219** **Cassini-Huygens Maneuver Automation for Navigation**
Troy Goodson, Amy Attiyah, Brent Buffington, Yungsun Hahn, Joan Pojman, Bob Stavert, Nathan Strange, Paul Stumpf, Sean Wagner, Peter Wolff, Mau Wong, Jet Propulsion Laboratory

Many times during the Cassini-Huygens mission to Saturn, propulsive maneuvers must be spaced so closely together that there isn't enough time or workforce to execute the maneuver-related software manually, one subsystem at a time. Automation is required.Automating the maneuver design process involved close cooperation between teams. We present the contribution from the Navigation system.
In scope, that includes trajectory propagation and search, generation of ephemerides, general tasks such as email notification and file transfer, and presentation materials.
The software has been used to help understand maneuver optimization results, Huygens probe delivery statistics, and Saturn ring-plane crossing geometry.

14:45 **AAS 06 - 220** **Launch Navigation Support for Mars Reconnaissance Orbiter**
Neil A. Mottinger, Jet Propulsion Laboratory, California Institute of Technology

This paper describes the preparation for navigation support during the critical launch phase of the Mars Reconnaissance Orbiter. Careful and thorough initial acquisition planning for DSN and non-DSN (JAXA) stations was very important due to 1) unique characteristics of the departure trajectory, 2) launch capabilities of the Atlas Centaur vehicle, 3) pointing accuracy requirements of the DSN stations, and 4) the sequence and variations in which DSN stations and /or complexes acquire the downlink and uplinksignal within the daily launch windows and across the entire launch period. The orbit estimates obtained using DSN and JAXA tracking data are reviewed.

15:10 **Break**

15:30 **AAS 06 - 221** **Liaison Navigation in the Sun-Earth-Moon Four-body Problem**
Keric Hill, University of Colorado

Liaison Navigation involves the use of scalar satellite-to-satellite tracking data to autonomously determine the orbits of a spacecraft constellation. It was shown that Liaison Navigation worked well for spacecraft in halo orbits in the Earth-Moon three-body problem. In this paper, Liaison Navigation is simulated using libration orbits in the bicircular four-body problem involving the Earth, Moon, and Sun. The effects of the fourth body and solar radiation pressure on the orbit determination accuracy of the constellation are reported. Navigation accuracy with a standard deviation on the order of 10 m could be achievable in actual operations using Liaision Navigation.

15:55 **AAS 06 - 222** **Interferometer technique for initial orbit determination and orbit monitoring**
M Di Ruscio, F. Longo, CRPSM - University of Rome "La Sapienza"

This paper analyses the problem of the initial orbit determination using a two antennas interferometer technique (for ranging measurements) and antennas pointing angles. The interferometer technique measures the interference (phase difference) between the radio signals, generated by a spacecraft, received by two different antennas. An analysis about the accuracy of ranging, elevation, azimuth and the rates of each measurement, has been carried out. To validate this model, real-time data are used from various satellites acquired by two S-band antennas located in the “Broglio Space Centre” (Malindi, Kenya), and the results are compared with precise orbit ephemeris.

16:20 **AAS 06 - 223** **The JPL Roadmap for Deep Space Navigation**
Tomas J. Martin-Mur, JPL

This paper reviews the set of deep space missions that will be supported by NASA’s Deep Space Mission System in the next twenty five years, and extracts the driving set of navigation capabilities that these missions will require. There will be many challenges including the support of new mission navigation approaches such as formation flying and rendezvous in deep space, low-energy and low-thrust orbit transfers, precise landing and ascent vehicles, and autonomous navigation. Innovative strategies and approaches will be needed to develop and field advanced navigation capabilities.

Jan 25, 2006

Session 18: Solar Sails and Tethers

Chair: Professor Peter Bainum
Howard University

13:30 **AAS 06 - 224** **Structural Dynamics of a Spin-Stabilized, Mast-free Solar Sail Design**
Thierry Botter, University of Illinois

The time-varying motion of a spin-stabilized, mast-free solar sail design has been investigated. The derived dynamic model was solved using both computer simulations and analytical methods. Three specific scenarios were studied: the transient response ofan ideal sail to pitch maneuvers, the steady-state shape of a Sun-facing blade, and the combined, global motion of a sail due to controlled pitching at the tip. Results indicate that matched damping is necessary for quick and accurate sail responses, andthat the steady-state acceleration of such a design would be 5.67mm/s^2.

13:55 **AAS 06 - 225** **Solar Sail Navigation: Estimation of Force, Moment, and Optical Parameters**
Leonel Rios-Reyes, Daniel Scheeres, University of Michigan

Determining a solar sail's propulsion model on the ground is an inherently dificult task. Uncertainties in the sail shape are always present since the sail's precise curvature and surface structure may change after deployment in space. For accurate navigation, it is essential that the post-launch sail propulsion model is estimated. In this paper, we provide a methodology for estimating the force and moment generated by a sail of arbitrary, but constant, shape based on in-flight data. This is accomplishedby finding the force and moment tensor coefficients defined by the generalized sail model, which models the propulsion characteristics of solar sails with arbitrary shapes.

14:20 **AAS 06 - 226** **Sensitivity Studies of the Deployment of a Square Inflatable Solar Sail with Vanes**
Marco B. Quadrell, John West, Jet Propulsion Laboratory

This paper summarizes the result of numerical experiments to determine the sensitivity of the final attitude of an inflatable solar sail to various parameters affecting the deployment process. These parameters are: length inflation profile, and vane deployment failures. We show how robust the sail deployment is to geometric asymmetries before a 35 degree Sun angle is reached. Differential delays in the time to inflate the booms and a boom sweep-back angle affect the stability favorably. Adjacent vane failures to deploy affect the stability unfavorably, while the failure of opposing vanes is acceptable. Realistic boom length rate profiles obtained during ground tests are used in the simulation, showing that failing adjacent vanes in conjunction with initial inflation delays in adjacent booms represent the worst case.

14:45 **AAS 06 - 227** **Effects of the Space Elevator Dynamics on the Orbit of a Launched Satellite**
Stephen Cohen, Arun K. Misra, McGill University

The space elevator offers an alternative method of transporting satellites into space. Once the many challenges facing the deployment of a space elevator have been resolved, an important issue will be to understand the system’s dynamics. This paper attempts to develop a realistic and yet simple planar model for this. Once the dynamics of the system have been analyzed, the effects of this motion on the orbit of a satellite, when it is launched from the elevator, are investigated.

15:10 **Break**

15:30 AAS 06 - 228 Invariant Shape Solutions of Spinning Three Craft Coulomb Tether Problem

Islam I. Hussein, University of Illinois, Urbana-Champaign; Hanspeter Schaub, Virginia Tech

We study shape-preserving formations of three spacecraft, where the formation keeping forces arise from the electric charges deposed on each craft. Inspired by Lagrange's three-body problem, we derive general conditions that guarantee preservation of thegeometric shape of the formation. We show that while the classical collinear configuration is a solution to the problem, the equilateral triangle configuration is not. Hence, we analyze the three collinear spacecraft problem and categorize the solutions based on the spacecraft mass-charge ratio. Finally, the boundedness of the collinear solution is studied.

15:55 AAS 06 - 229 Reconfiguration of a 2-Craft Coulomb Tether

Arun Natarajan, Hanspeter Schaub, Virginia Tech; Gordon G. Parker, Michigan Tech

The linear dynamics and stability analysis of reconfiguring a 2-spacecraft Coulomb tether is investigated. Here the relative distance between the two satellites is increased or decreased using electrostatic Coulomb forces. The two craft are connected byan electrostatic tether which is capable of both tensile and compressive forces. As a result, the two-craft formation will essentially act as a long, slender, nearly-rigid body of variable length. Inter-spacecraft Coulomb forces cannot influence the inertial angular momentum of this formation. However, the gravity gradient effect can be exploited to stabilize the attitude of this Coulomb tether formation about an orbit radial direction.

Jan 25, 2006

Session 19: Martin Lo Tutorial -1

Chair: Rao Vadali
Texas A&M University

15:10 **Break**

Jan 26, 2006

Session 20: Surveillance and Space Debris

Chair: TS Kelso
CSSI

08:00 **AAS 06 - 230** **Constellations Using Entry Pupil Processing for High Resolution Imaging of Geosynchronous Objects**

David C. Hyland, Texas A&M University

This paper investigates the design of a LEO-based observatory of small telescopes using the Hanbury Brown-Twiss effect to achieve ultra-fine resolution imaging (down to 1 cm) of GEO objects. The observatory consists of a string of small spacecraft, all inthe same, circular, approximately polar, LEO orbit and each equipped with the necessary telescopic and photometry equipment. The spacecraft are positioned so that as few relative position baselines as possible are repeated for the given number of spacecraft. For such configurations, we establish the tradeoffs between image quality, number of spacecraft, telescope parameters and observation time.

08:25 **AAS 06 - 231** **Space Surveillance using Star Trackers. Part I: Simulations**

Iohan Ettouati, Daniele Mortari, Thomas Pollock,Texas A&M University

Performing Space Surveillance using Star Trackers is a new concept. This paper begins with the developement of software reliable enough to simulate accurately the image taken by a Star-Tracker. An image is then taken according to a visibility condition. During the time of integration TOI, the position and attitude of both spacecraft vary which influences the position of the target on the CCD and its apparent magnitude. A Gaussian distribution is then used to spread the energy on the image. Acquisition and centroiding are performed with the Run Length Encode RLE, using recursive functions. Then, star-identification and/or estimation can begin and one can get an accurate idea of whether the object is detectable.

08:50 **AAS 06 - 232** **Space Surveillance Using Star Trackers: Orbit Estimation**

Ossama Abdelkhalik, Daniele Mortari, John L. Junkins, Texas A\&M University

The problem of estimating the orbit of a space object using star tracker measurements is addressed. Star trackers can provide azimuth and elevation measurements of a space object which are used to estimate the orbit of the object, assuming the motion model is known. The system observability is investigated. Both batched least square and Kalman filter techniques are implemented. Results show that the orbit parameters of the target object can be estimated if the measurements time span is in the order of 20%of the orbital period.

09:15 **AAS 06 - 233** **Covariance as a Metric for Catalog Maintenance Error**

A.M. Segerman, AT&T Government Solutions; K.A. Akins, Naval Research Laboratory

An evaluation is performed of the ability to use the covariance from special perturbations orbit determination as a metric for actual orbit error. A software tool has been developed which statistically examines the covariance matrix from catalog maintenance, and determines how well the covariance represents the error as compared to available reference orbits, allowing easy recognition of unexpected covariance values. Various techniques are evaluated for use with objects for which reliable reference orbits are not available. Statistical results are presented, along with an evaluation of the usefulness of the covariance as a metric for catalog maintenance.

09:40 **Break**

10:00 **AAS 06 - 234** **Progress in International Space and Astrodynamics Standards**
David Finkleman, Analytical Graphics, Inc.

This paper will report advances in standardizing astrodynamics and space operations. "Space Systems — Orbital Debris — Part 1: Management for Debris Prevention and Mitigation"is the overarching guidance. It cites actions such as launch and on orbit collision avoidance. These actions devolve into supporting standards, such as assessing collision probabililty, determining continuously the energy content of satellites, or disposing of mission ended satellites. Those standards are further decomposed into the manner in which orbits may be described and the content and format of data exchange among involved parties. The approach is to build up from the lowest level until the entire pyramid is populated.

10:25 **AAS 06 - 235** **Space Vehicle Conflict Avoidance Analysis**
Russell Patera, Center for Orbital and Reentry Debris Studies, The Aerospace Corporation

Uncertainty in state vector positions and hard body sizes of tracked space objects makes the collision avoidance decision problematic. The concept of conflict prediction and resolution is adopted from the aviation community to remedy the situation. Small hard body sizes used in collision probability are replaced with a single much larger conflict volume that is independent of actual hard body sizes. As a result, conflict probability values are much large and more easily interpreted that collision probability values. A method of computing a conflict avoidance or conflict resolution maneuver threshold is presented. Conflict probability is compared to collision probability for several conjunctions.

10:50 **AAS 06 - 236** **The Efficient Analytic Computation of Fractional Reentering Debris from an Idealized Isotropic Explosion in General Elliptic Orbit**
Jean A. Kechichian, Marlon E. Sorge, The Aerospace Corporation, Los Angeles, California

The efficient computation of the fraction of debris from an isotropic explosion in general elliptic orbit, which would fly in orbits whose perigees are below a certain given altitude that usually corresponds to the atmosphere interface is presented. Givenan explosion velocity, a spacecraft idealized as a sphere breaks up into small fragments that either stay in earth orbit or intersect the atmosphere interface resulting in reentry. The locus of points on the surface of the sphere that separates the two groups of debris is obtained analytically in the form of a quartic, and the corresponding areas are evaluated by Gaussian quadrature for accurate percentage counts.

11:15 **AAS 06 - 237** **Improvements in Modeling Thermospheric Densities Using New EUV and FUV Solar Indices**
Bruce R. Bowman, Air Force Space Command

Major improvements in empirical thermospheric density modeling using new solar irradiance indices are reported. The development of a new solar extreme ultraviolet (EUV) irradiance index and a new far ultraviolet (FUV) Schumann-Runge Continuum (SRC) indexare described. We show major improvements in satellite drag modeling by incorporating the new EUV index derived from SOHO data, and the new SRC index derived from UARS and SORCE observations.

Jan 26, 2006

Session 21: Martin Lo Tutorial -II

Chair: Paul Schumacher
Naval Network and Space Operations Command

09:40 **Break**