13th AAS/AIAA

Space Flight Mechanics Conference

Ponce Hilton Hotel
Ponce, Puerto Rico

February 9–13, 2003

PROGRAM

	General Chairs	**Technical Chairs**
AAS	Dr. Ronald Proulx Charles Stark Draper Laboratory	Dr. Daniel J. Scheeres The University of Michigan
AIAA	Dr. Al Cangahuala Jet Propulsion Laboratory	Dr. Mark E. Pittelkau Applied Physics Laboratory

CONTENTS

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MEETING INFORMATION

Registration

The following registration fees will be in effect for this conference:

AAS or AIAA Members	US$225
Nonmembers (includes 1 year membership in AAS)	US$310
Students	US$50

Registration and payment will be only on-site. No pre-registration is available. Please pay cash (US dollars) or make checks drawn on a US bank payable to *American Astronautical Society*. The registration desk will be open in Caribe A, at the following times:

Sunday evening	4:00 PM – 7:00 PM
Monday–Wednesday	7:00 AM – 4:00 PM
Thursday	7:00 AM – 11:00 AM

A map of the conference facilities is shown on page 71 of this document, and the program summary is shown on page 72.

Conference Proceedings

The proceedings will be available to attendees of the conference at a reduced pre-publication cost of US$190. Orders for the conference proceedings will be accepted at the time of registration. After the conference the proceedings will approximately double in cost. Please pay cash (US dollars) or make checks drawn on a US bank payable to *American Astronautical Society*.

Special Events

Sunday: For early registrants, there is an Early Bird Reception at the hotel from 6:00–9:00 PM.

Monday: The Brouwer Award Lecture will be held in Gran Salon C from 5:00–6:00 PM. This will be followed by a General Reception from 6:30–9:00 PM in the Gran Salon B+3+4.

Tuesday: Dr. Daniel R. Altschuler, director of the Arecibo Observatory, is our guest speaker from 5:00–6:00 PM. Afterwards all attendees are invited to enjoy a poolside barbeque at 6:30 following Dr. Altschuler's presentation.

Wednesday: This evening is free for enjoying the local restaurants, shops, and the beach.

Thursday: Field trip to the Arecibo observatory. Departure on bus from hotel after the morning sessions at around 12:00. Arrive at Arecibo around 2:00 and return by 6:00. Exact departure and arrival times will be announced at the conference.

Please address questions or comments to one of the General Chairs listed on page ii.

TECHNICAL PROGRAM

Technical Sessions

There are twenty-one technical sessions scheduled over a three and a half day period with a total of 150 papers on the agenda. The technical sessions will run in parallel with three morning sessions and three afternoon sessions. All technical sessions will be held in Conference Center I, Caribe B, and C starting at 8:00 AM and 1:30 PM each day. Morning and afternoon breaks will be held midway through each technical session. Up to 9 papers will be presented in each session, though most sessions are shorter. The presentation time is 20 minutes, including 5 minutes for questions.

Speakers' Briefings

Authors who are making presentations and session chairs will meet for a short briefing on the morning of their session at 7:00 AM in Salon 5+6. A continental breakfast will be served. *Only the presenters of the day shall attend the breakfast.*

Paper Presentations

Presentations are scheduled for 20 minutes each: 15 minutes for the presentation and 5 minutes for questions. This schedule will be strictly enforced so that attendees may schedule their time between parallel sessions. Please note that a strict **NO PAPER, NO PODIUM** rule wil be enforced, i.e., speakers will not be allowed to present their paper if they have not provided 50 copies of their paper.

Paper Sales

Authors are required to bring 50 copies of their paper to the conference. The preprints will be on sale for US$2.00 per paper in Caribe A. Bound copies of the proceedings may be ordered at the registration desk.

Committee Meetings

Committee meetings will be held during the lunch break in the Salons 5+6 according to the following schedule:

AIAA Astrodynamics Technical Committee	Monday	11:30 AM – 1:30 PM
AAS Space Flight Mechanics Technical Committee	Tuesday	11:30 AM – 1:30 PM
AAS Space Flight Mechanics Tech Committee (II)	Wednesday	11:30 AM – 1:30 PM

Volunteers

Volunteers are needed to work at the registration desk and in the paper sales room. If you wish to be an early volunteer, please contact one of the chairpersons listed on page ii.

Please address questions on the Technical Program to one of the Technical Chairs listed on page ii.

CONFERENCE LOCATION

Ponce, Puerto Rico

Located on the southern shore of Puerto Rico in Ponce, the hotel is situated on beautifully landscaped grounds, facing the Caribbean Sea, with spacious guest rooms, many with private balconies overlooking the gardens or the ocean. Guests can enjoy casino action, international and local cuisine at two restaurants, bars, swimming pool, tennis courts, fitness center and golf practice range.

The property borders the black sand beaches typical of southern Puerto Rico, and is located 11 kilometers (7 miles) from the center of Ponce, Puerto Rico's second largest city. This majestic city, founded in the 16th century and restored to its former feudal days, is one of the Caribbean's best examples of neo-classical, rococo, and Creole Spanish Colonial architecture. The hotel features a modern tropical architectural design with ample halls, lobby, cascading waterfalls and a three story high atrium. The Ponce Hilton has contains two restaurants, three bars, the Pavilion Discotheque, and the largest Casino in the southern part of Puerto Rico. Los Balcones Bar and La Bohemia Cocktail Lounge entertain with live music on weekends.

Day trips to Caja de Muerto (Coffin) island are available, via concessionaire, for snorkeling and scuba diving. About 45 minutes away is the Bioluminescent Parguera Bay, best observed in the evening after sunset. The Arecibo Observatory is located northwest of Ponce, 1 1/2 hours away via twisting mountain road, and 3 hours away via the coastal route.

Accommodations

The cutoff date for making reservations at the conference rate is January 24, 2003. A block of rooms has been reserved for the conference at the conference hotel

The Ponce Hilton and Casino
1150 Caribe Avenue
Ponce, Puerto Rico, 00731

at the following rates, which will be honored three days before and after the conference dates, subject to availability.

Conference Rate:	US$150.00
US Government/Military:	US$129.00

Reservations should be made directly to the Hilton Ponce and Casino.

Telephone	(787) 259-7676 x5870
	(800) 981-3232
Fax	(787) 259-7674

To obtain the conference rate when making reservations, please be sure to mention that you are attending the 2003 AAS/AIAA Space Flight Mechanics Meeting.

Terms: Check-in after 3:00 PM, check-out by 12:00 noon, deposit required, major credit cards are accepted by the hotel. Check with the hotel for individual cancellation policies.

Transportation

Puerto Rico is conveniently reached through the Luis Munoz Marin International Airport in San Juan. This destination is served by numerous US Airlines. Flight times from some major cities in the world to San Juan are: Los Angles, CA (8 1/2 hrs); Boston, MA (4 hrs); Detroit, MI (4 1/2 hrs); Madrid, Spain (7 1/2 hrs); Frankfurt, Germany (9 hrs); and Buenos Aires, Argentina (7 hrs). For about US$100 (round trip) additional cost, you may fly the short hop to the Ponce Mercedita Airport, about 7 kilometers from the hotel.

Car rentals are available at the airport in San Juan; it takes about 1 1/2 hours to drive from there to the Ponce Hilton through the mountainous center of Puerto Rico on well-maintained roads. If driving, take the exit to the Teodoro Moscoso Bridge; stay on Hwy 17. After the 4th traffic light go underneath Hwy 18, and take it due south. Keep on left lane to exit to Caguas Hwy 52, leading directly to Ponce; exit to route 14 and turn left at 1st light. Taxi service from the San Juan airport to the hotel is available for about US$100.

Hotel Area Map

Ponce Street Map

Puerto Rico Map

PROGRAM SUMMARY

Date/Time	Event	Location
Sunday, 9 February		
1600–1900	Conference Registration	Caribe A
1900–2200	Early Bird Reception	Gran Salon A+1+2
Monday, 10 February		
0700–1600	Conference Registration	Caribe A
0700–0800	Speakers' Breakfast	Salon 5+6
0800–1700	Paper Sales	Caribe A
0800–1110	Sessions 1, 2, 3	Conference Center I, Caribe B and C
1130–1330	Lunch	
1130–1330	AIAA Astrodynamics TC Meeting	Salon 5+6
1330–1640	Sessions 4, 5, 6	Conference Center I, Caribe B and C
1700–1800	Brouwer Award Lecture	Gran Salon C
1830–2100	General Reception	Gran Salon B+3+4
Tuesday, 11 February		
0700–1600	Conference Registration	Caribe A
0700–0800	Speakers' Breakfast	Salon 5+6
0800–1700	Paper Sales	Caribe A
0800–1110	Sessions 7, 8, 9	Conference Center I, Caribe B and C
1130–1330	Lunch	
1130–1330	AAS Space Flight Mechanics TC Meeting	Salon 5+6
1330–1640	Sessions 10, 11, 12	Conference Center I, Caribe B and C
1700–1800	Guest Speaker from Arecibo Observatory	Gran Salon C
1830–2300	Poolside Barbecue	Poolside
Wednesday, 12 February		
0700–1600	Conference Registration	Caribe A
0700–0800	Speakers' Breakfast	Salon 5+6
0800–1700	Paper Sales	Caribe A
0800–1110	Sessions 13, 14, 15	Conference Center I, Caribe B and C
1130–1330	Lunch	
1130–1330	AAS Space Flight Mechanics TC Meeting II	Salon 5+6
1330–1640	Sessions 16, 17, 18	Conference Center I, Caribe B and C
Thursday, 13 February		
0700–1100	Conference Registration	Caribe A
0700–0800	Speakers' Breakfast	Salon 5+6
0800–1100	Paper Sales	Caribe A
0800–1110	Sessions 19, 20	Caribe B and C
1200–1800	Tour Arecibo Radio Observatory	Meet in Hotel Lobby for departure

BROUWER AWARD LECTURE

Monday, 10 February, 1700–1800, Gran Salon C

Roger A. Broucke

University of Texas

AAS 03-148

A HALF A CENTURY OF ASTRODYNAMICS

I will review of the field of Astrodynamics and/or Celestial Mechanics during the last 50 years. It has now been 45 years since the launch of the first Sputnik, October 4 1957, but there were already some published papers in the field a few years earlier. So, I believe I am justified to call this a half century. I illustrate the new problems, the new methods and the most significant contributions that faced the first half-century.

I will first enumerate a few problems originating with the artificial satellites and with the availability of new types of very accurate observations such as Ranging and Doppler, first with radar, later with laser. This has resulted in the refinement of least squares methods, and the processing of continuous streams of data with sequential algorithms such as the Kalman filter. Another resulting new problem is the need for accurate models of the Earth's atmosphere.

One of the most important problems is to determine accurately the gravity field of the Earth in terms of Spherical Harmonics. One of the outgrowths is the appearance of many new artificial satellite theories, such as by Brouwer, Garfinkel, Hori, Vinti, and Aksnes. A fundamental concept here is the critical inclination that was discovered in the beginning of the space age. Besides the gravity field of the Earth, new methods for the gravity of asteroids and highly irregular shaped bodies have been devised and the polyhedron method was refined by Bob Werner.

The space age also brought the need for more accurate ephemerides of the moon and the planets, leading to important work to improve the Astronomical Constants as well as new accurate theories, both analytical and numerical, for the planets and the natural satellites.

The space age also motivated a vast amount of theoretical researches in the last 50 years. For instance our understanding of resonances in the solar system has greatly improved. This includes a better understanding of the Kirkwood gaps in the Asteroid belt as well as the discovery of the Neptune-Pluto resonance. Other popular problems are the three-body problem, both restricted (circular and elliptic) as well as general, also in conjunction with regularizations, such as the new KS transformation. Only during the space age have we really started the exploration of three-dimensional orbits and the so-called Halo orbits. One of the most useful concepts of the three body problem in planetary explorations is certainly the slingshot or gravity assist concept.

Of course, with the appearance of new problems come many new methods for solving them. For instance, we have averaging, better numercal integration methods, higher order Runge Kutta algorithms, symplectic integrators, computerized Poisson series and general algebraic manipulations, (Mathematica). Much progress has been made as well in the use of Hamiltonian Dynamics such as for instance Hori and Deprit with the use of Lie series expansions.

I believe that one must also mention the great progress in one of our most important tools: the computer, noting that one of the first important commercial computers came simultaneously with Sputnik. I believe that we must trace the evolution of the speed of these computers because all our trajectory integrations depend on this. I will illustrate my lecture with some computer animations.

GUEST SPEAKER FROM ARECIBO OBSERVATORY

Tuesday, 11 February, 1700–1800, Gran Salon C

Daniel R. Altschuler

Director, Arecibo Observatory

AAS 03-256

The Arecibo Observatory—History and Science

The Arecibo Observatory in Puerto Rico was innaugurated in 1963. Almost 40 years later it is still the largest single dish rediotelescope on Earth. After two upgrades, it continues to be a very productive instrument. It's history and some of its major achievements are presented.

Daniel Altschuler is author of the recent book "Children of the Stars" edited by Cambridge University Press. This book will be available at $25.

Session 1: Attitude Control

Chair: Ron Lisowski
US Air Force Academy

0800 AAS 03-100

Integrated Orbit and Attitude Control for a Nanosatellite with Power Constraints

M. M. Berry, B. J. Naasz, H.-Y. Kim, and C. D. Hall; Virginia Tech

Small satellites tend to be power-limited, so that any actuators used to control the orbit and attitude must compete with each other as well as with other devices for electrical power. The Virginia Tech nanosatellite project, HokieSat, must use its limited power resources to operate pulsed-plasma thrusters for orbit control and magnetic torque coils for attitude control, while also providing power to a GPS receiver, a crosslink transceiver, and other subsystems. In this paper we describe our strategy for integrating these two control systems and present results of simulations developed to verify the strategy.

0820 AAS 03-101

An Integrated Structural and Control Optimization Approach for a Space Station Design

Ijar M. Fonseca and Peter M. Bainum; Howard University

This work concentrates on a flexible space station model with two solar arrays and a robotic manipulator. The system equations are written in terms of the thicknesses of the structural elements, which are the design parameters in the optimization process. The optimization process is implemented numerically by using existing software from the control and the structural areas. The results for a large space station reflect mass (weight) reduction as well as in the reduction of the control effort to control the rotational vibrational motion.

0840 AAS 03-102

A Cost Function for Bang-Off-Bang Control of Axisymmetric Spacecraft

R. A. Hall and N. C. Lowry; Charles Stark Draper Laboratory

A cost function to minimize propellant usage for bang-off-bang attitude control of axisymmetric spacecraft is introduced. The cost function, implemented in a feedback control algorithm, allows one to determine a minimal fuel trajectory to achieve reorientation. Cost functions are defined for Euler Axis rotations, 'Torque Free' rotations, and three pulse rotations. It is demonstrated that use of the cost function can result in significant savings in propellant usage.

0900 AAS 03-103

Structured Model Reference Adaptive Control For Vision Based Spacecraft Rendezvous And Docking Problem

Puneet Singla, Declan Hughes, J. L. Junkins; Texas A&M University, College Station

A structured model reference adaptive control law has been developed for vision based spacecraft rendezvous and docking problem. A highly accurate relative motion of chaser spacecraft can be estimated by processing the reliable high bandwidth measurements of newly developed VISNAV sensor through a Kalman filter. The adaptive control law formulation is based upon the Lyapunov's direct stability theorem and imposes the exact kinematic equations at velocity level while taking care of model uncertainties and disturbances at acceleration level. The essential ideas and results from computer simulations are presented to illustrate the algorithm developed in paper.

Break **0920–0950**

0950 AAS 03-104

The Effects Of Averaging In Real Time Matched Basis Function Repetitive Control

Masaki Nagashima and Richard W. Longman; Columbia University

Internal moving parts such as reaction wheels or control moment gyros in spacecraft create vibrations. Matched basis function repetitive control can attenuate the effects of such vibrations at the location of some fine pointing instrument. This method must identify in real time the components of the error at the frequencies of these disturbances. In practice there will be other disturbance frequencies from other sources. This paper studies the use of averaging as a method of isolating the frequencies of interest, and preventing cross talk – disturbance of the addressed frequencies by the unaddressed frequencies, and vise versa. It is seen that averaging can significantly assist the disturbance from unaddressed to addressed. But there is a waterbed effect even in this case of linear equations with periodic coefficients, that says the improvement at one frequency must be paid for at some other frequency. Thus, there is a fundamental limitation when trying to decouple the influence of addressed to unaddressed disturbance frequencies.

1010 AAS 03-105

Finite Time Equivalent Of Zero-Phase Frequency Cutoff For Robustness In Learning Control

Kenneth Chen and Richard W. Longman; Columbia University

Iterative learning control aims to eliminate tracking error in hardware by learning from previous experience with the tracking command. Mathematical proofs can be given to show convergence to zero error independent of the system dynamics, eventually learning whatever is needed. However, in practice the learning transients can be prohibitively bad. A very practical solution is to make use of a zero-phase low-pass filter cutoff of the

learning. This works very well in a majority of applications, but it relies on steady state frequency response thinking. In spacecraft maneuvers attempting to perform precision motion at high speed, spacecraft flexibility causes serious difficulties. One wants to have a learning process that has robustness of the good learning transients associated with a frequency cutoff, and at the same time the maneuver must be accomplished in a time too short to have frequency response modeling apply. This paper develops the analog of a frequency response cutoff for short trajectories, and creates associated learning laws.

1030 AAS 03-106

Adaptive Inverse Iterative Learning Control

Richard W. Longman and Taekjoon Kwon, Columbia University; Yen-Tun Peng, National Taiwan University, Taiwan, ROC

Iterative learning control can be applied to make spacecraft perform precise tracking maneuvers, in spite of structural vibrations. Inverse control is a logical approach to try, finding the input associated with a desired output. But this process is usually an unstable one in digital systems. This paper investigates the use of system identification techniques to directly identify the inverse model. This is seen to be problematic due to instability, but it is shown that a fictitious direct feedthrough term can stabilize this. The methods are developed to use the identified inverse of the fictitious system to get the desired system inverse solution – bypassing the stability issue. In order to further correct tracking error, an adaptive inverse learning control is designed making rank one updates on the inverse model. Numerical simulations study the effectiveness of the approach.

1050 AAS 03-107

Repetitive Control To Eliminate Periodic Measurement Disturbances

Yi-Ping Hsin and Richard W. Longman; Columbia University

There are many spacecraft applications requiring fine pointing of equipment, that suffer from periodic disturbances form internal moving parts in the spacecraft. Repetitive control can be applied to this class of problems. This paper develops a new repetitive control structure designed to eliminate periodic errors in measurements, rather than to cancel periodic plant or output disturbances. This has application in eliminating encoder errors. By applying the feedback error as the input, the repetitive controller is able to learn to attenuate the repeatable measurement errors. The control system reacts based on the compensated measurement signal, improving the smoothness of path following. Experiments are performed on disk drives that demonstrate the effectiveness of the approach, producing an impressive 98% reduction in repeatable run out.

Session 2: Formation Flight-I

Chair: Craig McLaughlin
University of North Dakota

0800 AAS 03-108

Nonlinear Modeling and Control of Spacecraft Relative Motion in the Configuration Space
Pini Gurfil and N. Jeremy Kasdin, Princeton University

This paper presents a new methodology yielding high-order, nonlinear approximations to the relative orbital dynamics of spacecraft flying in formation. A nonlinear formation-keeping control law is then developed. Nonlinear models of relative spacecraft dynamics are parameterized as time-series. Instead of using the Cartesian initial conditions as constants of motion, classical orbital elements are utilized. Variation of these elements enables the incorporation of perturbations and control forces in a straightforward manner. The method presented in the paper does not require solution of the differential equations, thus offering a simple derivation of models for relative motion. The known inertial configuration space is utilized and projected onto a classical rotating Hill frame. Based on the nonlinear modeling, a globally asymptotically stabilizing low-thrust Lyapunov-based formationkeeping controller is developed. The merits of the proposed modeling and control are validated by a few illustrative examples.

0820 AAS 03-109

Linear and Nonlinear Control Laws for Formation Flying
S. S. Vaddi and S. R. Vadali, Texas A&M University

In this work, we analyze various control schemes for the control of formation flying satellites. The objective is to devise control strategies that can optimally generate circular or near circular relative orbits for large formations. Three types of controllers have been studied in this work. The Lyapunov controller offers global stability and zero steady state tracking errors but the associated control cost is very high. The LQR controllers guarantee only local stability but offer significant cost benefits. The period matching controllers exploit the existence of control free natural solutions and result in near circular relative orbits at a very low control cost.

0840 AAS 03-110

Coupled Orientation and Orbit Maintenance in Formation Flight via Sliding Mode Control
Yunjun Xu, Norman Fitz-Coy, University of Florida; Paul Mason, NASA/GSFC

To date, most formation flight investigations consider an uncoupled position and orientation model. In this paper, a scenario that couples the desired orientation of the satellites to their relative positions is investigated. Furthermore, a generalized dynamic model is adopted in which the satellites can be in any closed orbit. A sliding mode controller is designed and used to demonstrate the coupled orientation/position problem. This proposed controller is capable of maintaining the desired point orientation as well as the relative position continuously. The developed sliding model controller is also shown to reject model uncertainties related to the inertial matrix of the satellites.

0900 AAS 03-111

Deployment Of Spacecraft Large Formations

Giovanni B. Palmerini; Università di Roma ”La Sapienza”, Italy

Deployment of satellite formation leads to a trade-off between thrust needed and time requested to achieve the operational configuration. Autonomy, especially with large number of satellites involved, is also an interesting feature. Orbital planes different from the injection one should be usually reached, and this expensive manoeuvre could be accomplished making use of J2 effect. The paper introduces and solves the problem of the division of the platforms among drift orbits (partitioning problem). A two stages strategy (drift orbits for coarse phase and autonomous guidance using potential function for precise navigation) to acquire the desired configuration is presented. Examples of an Earth large constellation and of a Mars satellite network are carried on to show this strategy.

Break **0920–0950**

0950 AAS 03-112

Analytical Modelling and Control of Relative Orbits of Spacecraft Flying in Formation in LEO

T. Kormos and P. L. Palmer; Surrey Space Centre, University of Surrey, UK

This paper addresses the problem of formation flying modelling and control for LEO satellites. Unlike other approaches, which usually solve perturbed from of the Hills-Clohessy-Wiltshire equations, the relative orbits are derived geometrically using high accuracy analytical description of a single satellite (epicycle model). Using this analytic model we describe control schemes for maintaining the geometry of a formation of satellites against higher order perturbation in the geopotential. The accuracy of the system is demonstrated on a ring formation with an accuracy of around 0.1% of the ring radius.

1010 AAS 03-113

Control Strategies For Formation Flight In The Vicinity Of The Libration Points

K. C. Howell and B. G. Marchand; Purdue University

The concept of multiple spacecraft in formation flight offers many promising possibilities both for space exploration and the associated technology development. Much recent research has focused on formation flight for Earth-orbiting spacecraft. However, other mission scenarios have sparked new interest in formation flight in multi-body regimes, particularly, in the vicinity of the Sun-Earth libration points. The present study involves the application of existing control strategies, with appropriate modifications, to the multi-body problem. The goal is to maintain a constant separation and relative orientation between the chief and deputy spacecraft. Thus far, optimal control techniques (LQR) and a linear feedback controller based on Floquet theory have been implemented and tested on a multiple-spacecraft formation.

1030 AAS 03-114

Suppose A(t) Isn't Constant?
William E. Wiesel, Air Force Institute of Technology/ENY, Wright-Patterson AFB

The form of the solution for a general time-dependent linear system is explored, and some properties of Lyapunov transformations are reviewed. The solution of linear systems is intimately tied to a global separation of variables in the original system. A new definition of how the stability exponents propagate with time makes it possible to ensure that the transformation is always non-singular. Finally, a new definition of the optimal separation includes all known special cases of linear system solutions.

1050 AAS 03-115

Including Secular Drifts Into The Orbit Element Difference Description Of Relative Orbits
Hanspeter Schaub, ORION International Technologies

In recent developments an orbit element difference description has been introduced to describe the relative orbit geometry. Their structure is very similar to the solution of the circular chief orbit CW equations, but it can also scale easily to the eccentric chief orbit case. If the orbit element differences vary due to perturbations, then the orbit element difference differential equations would need to be integrated. This paper presents a method which avoids this numerical integration by finding analytical approximations to the orbit element difference drifts. With these formulas it is possible to directly describe the long term relative motion of spacecraft.

Session 3: Optimization

Chair: Jon Sims
Jet Propulsion Laboratory

0800 AAS 03-116

Probabilistic Optimization Applied To Spacecraft Rendezvous & Docking
Jeff M. Phillips, Lydia E. Kavraki, Rice University; Nazareth Bedrossian, The Charles Stark Draper Laboratory, Inc.

This paper presents a probabilistic approach to solve optimal control problems with application to spacecraft proximity operations. The 6 degree-of-freedom rendezvous and docking problem, using impulsive control, and avoidance of known obstacles and plume impingement is solved. Our solution is then extended to real-time obstacle avoidance. A feasible search space is developed with branch expansions using only controls and coasts, reducing search variables by nearly 50%. A randomized A* expansion technique explores the search space. A gradient descent approach avoids new obstacles in real-time by "stretching" the pre-computed optimal path in a locally optimal manner.

0820 AAS 03-117

Minimum-Time Orbital Phasing Maneuvers
C. D. Hall and V. Collazo Perez, Virginia Tech

The minimum-time, constant-thrust, orbital phasing maneuver is studied numerically. Non-dimensionalization reduces the problem to one where thrust magnitude and phase angle are the only parameters. Extremal solutions are obtained numerically for the entire range of practical values of thrust magnitude and phase angle. Plots of trajectories, thrust profiles, and loci of initial costates are used to identify a near-invariance principle that leads to a variety of conclusions about this class of problems.

0840 AAS 03-118

Optimal Rephasing Manoeuvre: Modelling And Applications
Chiara Valente, Dario R. Izzo, Università degli Studi di Roma "La Sapienza", Italy

A rephasing manoeuvre can be regarded as on orbital transfer in which the sole time of pericenter passage is changed. This kind of manoeuvre is usually accomplished via a so called Walking-Orbit. Recent result have showed that this elliptical transfer orbit is not the optimal solution to the problem. This remarkable counterexample of the apsidal line rule is here studied and a new algorithm that finds the optimal transfer orbit in the most general case is developed. The results show how the difference between the optimal

transfer orbit and the Walking Orbit is always quite small, but not negligible when the transfer orbit is completed a reduced number of times.

0900 AAS 03-119

Trajectory Optimization of a Constrained Mission about a Libration Point
Samantha Infeld and Walter Murray; Stanford University

Maintaining a trajectory in the vicinity of the unstable Sun-Earth L2 point is useful for certain scientific missions. Future missions of this nature will be more complex due to additional mechanical and mission constraints. Satisfying such constraints may be viewed as an optimization problem. It then adds little additional complexity to also minimize fuel usage. How to discretize the problem with the goal of creating a finite optimization problem with differentiable nonlinear constraints is analyzed. The methods and resulting optimization problems are presented. A simple case is studied as a preliminary step in creating an optimization method for libration-point missions.

Break **0920–0950**

0950 AAS 03-120

Trajectory Optimization for a Mission to NEOs, using Low-Thrust Propulsion and Gravity Assist
Mauro Massari, Politecnico di Milano, Italy; Massimiliano Vasile, ESA/ESTEC, The Netherlands; Franco Bernelli-Zazzera, Politecnico di Milano, Italy

This paper deals with the trajectory optimization, through a direct method, for a mission to NEOs, using low-thrust propulsion both for deep space navigation and for Earth escape phase, departing from an Earth orbit. The aim of the work is to demonstrate the possibility to realize a low-cost mission to reach NEOs. First the escape phase has been analyzed, from perigee raising to the border of Earth sphere of influence, verifying the possibility to use the Moon for a gravity assist maneuver. Then the deep space navigation phase has been analyzed considering also more than one NEO as targets.

1010 AAS 03-121

Optimal Interplanetary Trajectories to Mars Using Low-Thrust Engines
A. Miele, T. Wang, and P. Williams, Rice University

This paper deals with deep-space interplanetary flight to Mars using low-thrust electrical engines. Trajectory optimization is done via the sequential gradient-restoration algorithm (SGRA) for optimal control problems. The optimization criterion is the minimum propellant consumption.

Depending on whether we control only the thrust direction, or only the thrust magnitude, or both the thrust magnitude and direction, three continuous models are generated. An additional discrete model considers the alternation of thrusting sub arc-s and coasting sub arc-s. Results are presented and compared for all of the models.

1030 AAS 03-122

Fuel-Optimal Orbital Transfers for VASIMR-Powered Spacecraft
Hans Seywald, Analytical Mechanics Associates, Inc.

The Variable Specific Impulse Rocket (VASIMR) engine is an electric propulsion system that enables the user to vary the specific impulse within fixed bounds. Assuming constant power input, the resulting thrust is indirectly proportional to the chosen specific impulse. For these engine specifications, the optimal specific impulse function of time is determined such that a circular-to-circular low-thrust orbit transfer with prescribed transfer time is achieved with minimum fuel. This is achieved by analytically solving the associated optimal control problem. The interesting bottom line result is that the optimal specific impulse function of time varies linearly with time. As a result, the associated optimal thrust magnitude is then always proportional to the vehicle mass.

1050 AAS 03-123

Systems Analysis For Outer Planet Missions Using Solar-Electric Ion Propulsion
Mike Cupples and Shaun Green, Science Applications International Corporation;
Victoria L. Coverstone, University of Illinois at Urbana-Champaign

Systems analysis for solar electric ion propulsion based vehicles is performed. The analysis compares the vehicle performance for three solar-electric ion thruster models. Vehicle performance is derived from subsystem models of a solar electric propulsion system (SEPS) and a set of outer-planet trajectories that are generated to maximize the delivered mass to a designated outer planet. Two destinations, Saturn and Neptune, and the three thruster models are investigated. Insight is provided into the impact that mission difficulty, propulsion system Isp, array maximum power at 1 AU, thruster grid material, and number of thrusters will have on the SEPS vehicle performance based on metrics-of-merit such as payload to destination and ion propulsion system propellant throughput.

Session 4: Attitude Determination and Control–Hardware

Chair: Don Mackison
University of Colorado

1330 AAS 03-124

Integrated Power and Attitude Control for a Spacecraft with Flywheels and Control Moment Gyroscopes
Carlos M. Roithmayr, NASA Langley Research Center; C. D. Karlgaard, R. R. Kumar, D. M. Bose, Analytical Mechanics Associates Inc.

Laws are designed for controlling the attitude of an Earth-pointing spacecraft, and managing energy storage and angular momentum of flywheels and Control Moment Gyroscopes. General, nonlinear equations of motion are presented in vector-dyadic form, and then linearized in preparation for design of control laws that include feedback of flywheel kinetic energy error as a means of compensating for damping exerted by rotor bearings. Orientation can be controlled virtually inde.nitely about a torque equilibrium attitude, or held fixed until angular momentum saturation occurs. Results of numerical simulations are given, and show the amount of propellant that can be saved when flywheels assist the CMGs in holding the attitude of the International Space Station.

1350 AAS 03-125

Historical Review of Spacecraft Simulators
J. L. Schwartz and C. D. Hall, Virginia Tech, and M. A. Peck, Honeywell, Inc.

Air bearings have been used for spacecraft attitude determination and control hardware verification and software development for over 40 years. Test facilities are highly varied, ranging from simple university systems to robust government testbeds. Honeywell and Virginia Tech are each developing unique new facilities to complement the current infrastructure. During this development process, we have become interested in the history of these systems: how early systems were first devised, and what diverse capabilities current systems provide. We present a survey of spacecraft simulator laboratory systems that rely on air bearing technology.

1410 AAS 03-126

WITHDRAWN

1430 AAS 03-127

An Airbearing-Based Testbed for Momentum Control Systems and

Spacecraft Line of Sight
M. Peck, L. Miller, A. Cavender, M. Gonzalez, and T. Hintz; Honeywell, Inc.

The next generation of agile, precision spacecraft will demand novel approaches to attitude control and dynamics. The current paradigm of stiff, massive architectures is likely to give way to active/passive structural control of payloads with soft, well-damped bus-to-payload interfaces. Honeywell is developing a spacecraft attitude-dynamics testbed that is designed to assist in research and validation of hardware and software architectures for such spacecraft. The testbed offers high agilty (via six CMGs) and integrated structural control. The combination of a line-of-sight metrology system capable of sub-microradian resolution and a large range-of-motion spherical airbearing offers a unique environment for testing innovative spacecraft controls and dynamics concepts.

Break **1450–1520**

1520 AAS 03-128

User Interface Design for Moon-and-Star Night-Sky Observation Experiments
Christian Bruccoleri and Daniele Mortari, Texas A&M University

The proposed paper illustrates the user interface developed to perform ground tests night-sky experiment for star-tracker and Moon-Sun sensor. This interface allows communication between a notebook and a) one or two digital camera for Moon observation, b) a digital camera for star observation, c) a GPS receiver for timing and position determination, and d) the two motors of an equatorial mount to establish the orientation. Command and communication are performed via four different serial ports. In particular, some new general aspects related to star acquisition, centroiding, identification, and attitude and reliability estimations, as well as the Moon image data processing, are presented.

1540 AAS 03-129

WITHDRAWN

1600 AAS 03-130

Innovative Spacecraft Sun Acquisition Algorithm Using Reaction Wheels
Che-Hang Charles Ih and Richard A. Noyola, Boeing Satellite Systems

For sun acquisition using reaction wheels, the large maneuvers involved impose tremendous challenge upon the wheels due to the sun acquisition time constraint as well as the risk of wheel momentum saturation. If wheel saturation occurs during slew maneuvers, the path actually traced by the spacecraft will differ from the ideal path. This may result in failure to acquire the sun. If a fixed slew rate is intended to be used for all sun acquisitions, that rate has to be set conservatively low in order to insure no wheel saturates for a wide range of initial momentum states. It will lengthen the sun acquisition time significantly and may fail to meet the power safe time constraint requirement. This design solves both problems at the same time.

1620 AAS 03-131

Non Dimensional Star Identification for Uncalibrated Star Cameras

Malak A. Samaan and John L. Junkins; Texas A&M University

Star identification is an important process for any star tracker attitude determination sensor. The main purpose of the star identification is to identify the measured stars with the corresponding cataloged stars. Most star identification methods are depend on the star camera parameters, the focal length f and the focal plane offsets (xo, yo). But in many cases these parameters may not be accurate or the camera may not yet be calibrated. The non-dimensional starID method is the perfect way to identify the stars of uncalibrated or inacuarate parameters cameras. Of course this method is also works perfectly for calibrated star cameras. In this method we use the fact that the focal plane angles are independent of the focal length as well as principal point offsets. This method is very fast, easy to implement and very accurate with a probability of failed star ID less than 10^{-11}.

Session 5: Formation Flight-II

Chair: Jay Middour
Naval Research Laboratory

1330 AAS 03-132

Flying a Four-Spacecraft Formation by the Moon...Twice
J. J. Guzman and A. Edery; a.i. solutions, Inc.

Spacecraft flying in tetrahedron formations are excellent for electromagnetic and plasma studies. To better understand the Earth's magnetosphere and its interaction with the solar wind, the NASA Goddard Magnetospheric Multiscale (MMS) mission will fly a tetrahedron formation through different regions of the magnetosphere close to the magnetic equatorial plane. However, to explore regions that are almost perpendicular to the ecliptic plane a dramatic plane change is needed. To minimize fuel, a double lunar swingby can be used to perform the plane change. This paper investigates the feasibility of flying a four-spacecraft formation through the required double lunar swingby.

1350 AAS 03-133

Preliminary Planar Formation Flight Dynamics Near Sun-Earth L2 Point
A. M. Segerman, AT&T Government Solutions, Inc.; M. F. Zedd, Naval Research Laboratory

NASA is planning missions to the vicinity of the Sun-Earth L2 point, some involving a distributed space system of telescope spacecraft, configured in a plane about a hub. An improved understanding is developed of the relative motion of such objects in formation flight. The telescope equations of motion are written relative to the hub, and expanded in terms of the hub's distance from L2. A halo telescope orbit is investigated, with initial conditions selected to avoid resonance excitation. The accuracy of the resulting solution is presented.

1410 AAS 03-134

Relative Trajectory Analysis Of Dissimilar Formation Flying Spacecraft
Shankar K. Balaji and Adrian Tatnall, University of Southampton, UK

This paper deals with the analysis of the relative trajectory of spacecraft with small differential Drag- Area. The Equations for the relative coordinates are derived as a precise solution to the Formation geometry problem and are valid both for close and long distance Formation patterns and for rendezvous analysis. The coordinates of motion are propagated forward in time in the presence of perturbative forces for different altitudes. The individual and combined effects of the perturbative forces on different formation patterns are analysed. The results of this paper provide a physical insight into the actual behaviour of satellites in a cluster with differential Drag-Area.

1430 AAS 03-135

Modified Linear Approximation to the Classical Relative Motion Problem
Andrew Tatsch and Norman Fitz-Coy, University of Florida

In order to investigate various approach strategies, including but not limited to the co-orbit type, for the relative approach phase of an RVD process, guidance laws that are more robust than the linear approximation to the relative motion equations, i.e., Clohessy-Wiltshire equations, need to be developed. A modified form of the C-W equations are developed here that maintain the linear character but adds parameters to increase the fidelity. The modified C-W equations are then compared with the unmodified solutions via numerical simulations to validate the wider range of applicability and increased accuracy.

Break **1450–1520**

1520 AAS 03-136

Geopotential And Luni-Solar Perturbations In The Satellite Constellation And Formation Flying Dynamics
Edwin Wnuk and Justyna Kaczmarek, Astronomical Observatory of the Adam Mickiewicz University, Poznan, Poland

The paper concerns the theory of the relative satellite motion and takes into account all perturbation effects due to non-spherical geopotential and gravitational influence of the Sun and the Moon. The differential atmospheric drag and solar radiation effects are not included into the theory because typical formation flying missions are comprised of almost identical spacecrafts. The theory of relative motion is based on the second order theory of geopotential and luni-solar perturbations developed in the Astronomical Observatory in Poznan. It includes also the precise algorithm for the direct and inverse transformations between osculating and mean orbital elements. The theory uses nonsingular orbital elements and may be applied for different classes of orbits: from LEO to GEO. It can be used in different modes. In the averaged mode, when short-period effects are averaged and only the secular and long-period effects are taken into account, the relative satellite motion may be predicted for long time span. In the precise mode, when the relative motion between the chief and the deputy satellites is needed with a high accuracy, all the short and long-period differential perturbations are included.

1540 AAS 03-137

Formation Flying Satellites Baseline Accuracy Assessment Using DGPS
Frederic Pelletier, Canadian Space Agency; Stefano Casotto, University of Padua, Italy; Alberto Zin, Laben S.p.A., Italy

One of the challenges of a SAR interferometry mission in Low Earth Orbit is to determine with great accuracy the distances separating the satellites. This paper discusses the level of precision attainable in the LEO-LEO baseline estimation in the absence of inter-satellite ranging data. To take advantage of SAR measurements for interferometry, this baseline must be known to a few millimeters. To achieve this, GPS double differences using satellite-only links (i.e. GPS to LEO) were simulated together with measurement and model noise for a 1-km formation of two LEO. A least square estimation algorithm was then used to recover the data and estimate the baseline. The results are compared against the nominal "noise-free" estimate and are presented for different altitudes of interest, ranging from 400 to 800 meters.

1600 AAS 03-138

Cluster Orbits With Perturbations Of Keplerian Elements (COWPOKE) Equations

Chris Sabol, Air Force Research Laboratory, Kihei, HI; Craig A. McLaughlin, University of North Dakota

Relative equations of motions for space objects in non-circular orbits under the influence of perturbations have been derived using energy methods. While providing closed form analytic solutions in a transformed variable space are valuable for analysis, these approaches may be awkward for many applications since transformations are required to go from the canonical variable space to more traditional representations of satellite orbits such as Keplerian elements. Recent developments by the proposed investigators have indicated that it may be possible to express the relative equations of motion for space objects in non-circular orbits using mean Keplerian elements and low order expansions.

1620 AAS 03-139

Some Practical Aspects Of Spacecraft Formation Flying

Craig A. McLaughlin, University of North Dakota; T. Alan Lovell and Rob Howard, Air Force Research Laboratory

This paper introduces some practical issues for spacecraft formation flying. Some common formation designs based on Hill's equations are presented. These designs are then examined from the practical aspect of attaining them in the presence of non-circular reference orbits and Earth oblateness. Examples include the leader-follower, in-plane ellipse, and out-of-plane categories of formations. This paper will also look at the practical issues of formation reconfiguration and maintenance within the constraints of a realistic propulsion system.

Session 6: Optimization and Orbital Transfers

Chair: Prasun Desai
NASA Langley Research Center

1330 AAS 03-140

Guess Values for Interplanetary Transfer Design through Genetic Algorithms
Paola Rogata, Emanuele Di Sotto, Mariella Graziano, GMV S.A., Madrid

The design of an interplanetary transfer foresees the use of optimisation algorithms involving gradient computations. Their convergence or not to local minima depends upon initial guesses, which, generally, are difficult to identify. A global search technique, as a Genetic Algorithm, can be very useful. To use the genetic algorithms a proper cost function, providing the total mission delta-V, has been formulated. This is characterised by handling the different arcs defining the particular mission scenario including departure manoeuvre, deep space, fly-by with massive bodies and insertion manoeuvre at arrival.This paper reports the results obtained for several trajectories to both the internal and external planets. One interesting trajectory to Pluto is particularly highlighted in the paper.

1350 AAS 03-141

A Global Approach To Optimal Space Trajectory Design
Massimiliano Vasile, European Space Technology Centre (ESA/ESTEC), The Netherlands

In this paper a mixed approach combining a breaching technique and a particular implementation of evolution programming is proposed to solve some space trajectory design problems. This particular combination presents some novel ideas: a migration operator that guides individuals toward promising areas of the solution space, a filter operator (in place of common selection operators) ranking families of potentially interesting individuals and a particular tunneling technique used to find the global optimum. Moreover EP is used to obtain lower bound information, to select promising branches and to prune non-promising ones. Furthermore the algorithm treats both integer and real variables. The effectiveness of the proposed algorithm is demonstrated on some typical problems in space mission design.

1410 AAS 03-142

Adaptive Grids For Trajectory Optimization By Pseudospectral Methods
I. Michael Ross, Fariba Fahroo, and Jon Strizzi; Naval Postgraduate School

Recently, pseudospectral (PS) methods have been routinely used to solve complex trajectory optimization problems in a simple and efficient manner by way of the reusable software package, DIDO. While PS methods typically outperform other methods across a variety of performance metrics, the grid generated by a standard PS method is static leading to some wasteful accumulation of points at the ends. In this paper, we propose several new ideas leading to an adaptive grid. We propose a domain decomposition technique in defining "soft knots" and a domain transformation technique leading to non-polynomial basis functions. These two independent concepts can be combined to yield a unique approach to an adaptive grid for trajectory optimization. Finally, we show that the domain transformation approach satisfies a transformed version of the symmetric covector mapping theorem thus maintaining the useful properties of the original Legendre PS method. These ideas will be demonstrated by way of examples from astrodynamics.

1430 AAS 03-143

Design of a Multi-Moon Orbiter

Shane Ross, Wang Sang Koon, California Institute of Technology; Martin W. Lo, Jet Propulsion Laboratory; Jerrold E. Marsden; California Institute of Technology

The Multi-Moon Orbiter concept is introduced, wherein a single spacecraft orbits several moons of Jupiter, allowing long duration observations. The Delta-V requirements for this mission can be low if ballistic captures and resonant gravity assists by Jupiter's moons are used. For example, using only 22 m/s, a spacecraft initially injected in a Jovian orbit can be directed into a capture orbit around Europa, orbiting both Callisto and Ganymede enroute. The time of flight for this preliminary trajectory is four years, but may be reduced by striking a compromise between fuel and time optimization during the inter-moon transfer phases.

Break **1450–1520**

1520 AAS 03-144

Lunar Transfer Trajectory Design And The Four-Body Problem

James K. Miller, Jet Propulsion Laboratory

The existence of a ballistic trajectory from the Earth to orbit about the Moon was long considered to be impossible based on analysis of the three-body problem. In 1990 a ballistic trajectory from the Earth to lunar orbit was discovered while analyzing a plan to salvage the Muses A (Hiten) spacecraft. This trajectory utilized the Sun's gravity in conjunction with the Earth and Moon's gravity and was thus the first example of a practical four-body trajectory design. This paper presents a review of lunar transfer trajectories that go beyond three-body theory and the Jacobi integral. These include Hiten, Lunar A and the Genesis return trajectory from the vicinity of the Moon to Earth. It is shown that these trajectories may be analyzed by piecing together segments where three-body motion dominates.

1540 AAS 03-145

A Systematic Method for Constructing Earth-Mars Cyclers Using Direct Return Trajectories

Ryan P. Russell and Cesar Ocampo, University of Texas at Austin

A procedure for constructing ballistic Earth-Mars cycler orbits is presented. Solutions from the multiple-revolution Lambert problem are utilized to find free return Mars trajectories. These symmetric return orbits are patched to a sequence of full and half-revolution return orbits with gravity assist maneuvers at Earth. An algorithm is developed to minimize the required turning angles. The patched-trajectory is shown to be a cycler if its period is a rational multiple of the synodic period. The method generates many previously undocumented purely ballistic cyclers. Additional insight is sought by presenting results in a reference frame that fixes both Earth and Mars.

1600 AAS 03-146

Analytical Approximations for Planar High-Thrust and Low-Thrust Orbital Transfers

Hans Seywald, Analytical Mechanics Associates, Inc.

Analytical formulae are presented that approximate the evolution of the semi major axis, the maneuver time, and the final mass fraction for low thrust orbital transfers with circular initial orbit, circular target orbit, and constant thrust directed either always along or always opposite the velocity vector. For comparison, the associated results for high-thrust transfers, i.e. the two-impulse Hohmann transfer are summarized. All results are implemented in a computer code designed to analyze planar planetary and interplanetary space missions. As a numerical example, a mission from Low-Earth Orbit (LEO) to Jupiter's moon Europa is analyzed.

1620 AAS 03-147

Desensitized Optimal Trajectories with Control Constraints

Hans Seywald, Analytical Mechanics Associates, Inc.

In standard optimal control problem formulations, the task is to find the control functions that steer a given dynamical system to given boundary conditions such that a user-specified cost index is minimized. A clear disadvantage of this approach is that only the performance along the optimal solution is considered in the cost index. No attention is paid to how rapidly the performance degrades in the neighborhood of the optimal solution. The recently introduced concept called Desensitized Optimal Control (DOC) provides a framework that enables the inclusion of such sensitivities into the cost function. The current paper extends the DOC approach to problems with control constraints.

Session 7: Attitude Determination and Control - Missions

Chair: Al Treder
Dynacs Inc.

0800 AAS 03-149

MESSENGER Spacecraft Pointing Options

Dan O'Shaughnessy and Robin Vaughan, Applied Physics Laboratory

Planning is now underway for the MESSENGER mission to Mercury. Scheduled for launch in 2004, MESSENGER will orbit the planet for one Earth-year beginning in April 2009. A variety of different spacecraft attitudes are needed to support science observations, permit communication with Earth, and perform engineering activities. This paper presents the basic architecture of the on-board guidance system being implemented to generate desired (or commanded) spacecraft attitude and rate. Algorithms are given for the suite of base pointing commands and scan pattern combinations. The strategy for enforcing thermal safety constraints in the commanded attitude computation is described.

0820 AAS 03-150

CONTOUR's Phasing Orbits: Attitude Determination & Control Concepts and Flight Results

Jozef van der Ha, Gabe Rogers, Wayne Dellinger, James Stratton; Applied Physics Laboratory

The CONTOUR satellite was launched on July 3 2002 and placed in an Earth phasing orbit of 1.75-day period: it was kept in a spin-stabilized mode and its performance was flawless throughout the 6 weeks of phasing orbits. A large number of orbit and attitude maneuvers were executed in order to achieve the most beneficial orbit and attitude parameters during the SRM burn. The paper addresses the pertinent design concept and the observed in-flight performances of the spacecraft guidance and control capabilities that were operational during the phasing orbits.

0840 AAS 03-151

Acquisition, Tracking, and Pointing of Bifocal Relay Mirror Spacecraft

Brij N. Agrawal, Naval Postgraduate School

This paper presents the results of a research program for developing acquisition, tracking, and pointing of bifocal relay mirror spacecraft. The spacecraft consists of two optically coupled telescopes used to redirect the laser light from ground based, aircraft based, or spacecraft based lasers to distant points on the earth or in space. The spacecraft has very

tight pointing and jitter requirements, less than 144 nanorad for both telescopes. Because the two large telescopes are gimbaled, the spacecraft inertia has large variation during the large angle maneuvers. The attitude control systems consists of reaction wheels, start trackers, gyros, and sun sensors. Feed forward control and quaternion formulations are used. Kalman filter is used to update the rate gyros biases and the attitude angles during star tracker measurements. The telescopes have fast steering mirrors for fine pointing. Integration of spacecraft control is required to meet the performance requirements.

0900 AAS 03-152

In-Flight Performance and Calibration of the Autonomous Minisatellite PROBA

Jean de Lafontaine, Jean-Roch Lafleur, Isabelle Jean, Université de Sherbrooke; Pieter Van den Braembussche, Verhaert Design and Development nv, Belgium; Pierrik Vuilleumier, ESA/ESTEC, The Netherlands

In the context of its PRoject for On-Board Autonomy (PROBA), the European Space Agency is currently supporting the development of autonomy-enabling technologies for on-board mission management and payload operation. With the successful launch of the PROBA spacecraft on 22 October 2001, these technologies are now being evaluated in orbit. This paper presents the in-flight performance of the autonomous navigation, guidance and control functions of PROBA. It also gives the algorithms and results of the in-flight inertia tensor determination and payload alignment calibration. Due to the particular nature of the PROBA design, these algorithms required novel developments, discussed in the paper.

Break **0920–0950**

0950 AAS 03-153

Attitude Sensor Alignment And Calibration For The TIMED Spacecraft

Mark E. Pittelkau and Wayne F. Dellinger; Applied Physics Laboratory

This paper presents the attitude sensor alignment and gyro calibration for Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) and demonstrates the effectiveness of an Alignment Kalman Filter and a composite calibration algorithm. The on-orbit attitude determination performance prior to and after calibration is presented. The optical alignment performed prior to launch is compared to the estimated alignment parameters. Various means of validating the alignment calibration are discussed.

1010 AAS 03-154

Center of Mass Calibration of GRACE Mission

Furun Wang, Larry Romans, Byron D. Tapley, and Srinivas V. Bettadpur, University of Texas

The accelerometer on-board the launched GRACE satellite measures all non-gravitational accelerations, and also the disturbance accelerations. The accelerometer's proof mass offset from center of mass of satellite needs to be known and counteracted during the in flight phase in order to keep the disturbance accelerations as small as possible. In this paper, the real center of mass calibration of GRACE mission is designed and the real data processing is presented.

1030 AAS 03-155

Modeling, Analysis, and Testing for Nutation Time Constant Determination of On-Axis Diaphragm Tanks on Spinners: Application to the Deep Space One Spacecraft
Marco B. Quadrelli, Jet Propulsion Laboratory

This paper describes the analysis and testing done to determine the DS1 nutation time constant. Deep Space One was the first spacecraft flown by JPL with a diaphragm tank located on the spin axis. First, modeling considerations are presented and the dynamics of a rigid body coupled through a universal joint to a pendulum mass representing the liquid sloshing in the hydrazine tank is simulated. Second, the spin drop tests are described. The large value of the nutation time constant computed and verified by testing ensured that it remained well above the required values of 150 seconds at ignition, and 50 seconds at burnout.

1050 AAS 03-156

Modeling of MARSIS Segmented Booms and Prediction of In-Flight Dynamics of the Mars Express Spacecraft
Edward Mettler and Marco B. Quadrelli, Jet Propulsion Laboratory

This paper describes a dynamic analysis of the MARSIS Antenna booms deployed on the ESA Mars Express Spacecraft. The Mars Express Mission is a joint NASA/ESA Project to study Mars over a four year period. The Mars Advanced Radar for Subsurface and Ionospheric Mapping (MARSIS), provided by NASA/JPL, is a key instrument in the search for water. Spacecraft dynamical solutions involve coupled equations of motion for vehicle elliptical orbit mechanics, the rigid body spacecraft bus, and its flexible-appendages. Simulations of the orbiting spacecraft with the unique 60-meter MARSIS segmented dipole booms fully deployed verified modeling fidelity and provided data on dynamic interactions between the flexible booms and the spacecraft central body (or bus).

Session 8: Navigation and Control

Chair: Bobby Williams
KinetX, Inc.

0800 AAS 03-157

Numerical Solutions to the Small-body Hovering Problem
S. Broschart and D. J. Scheeres, University of Michigan

Mission proposals currently exist to visit small celestial bodies such as comets, asteroids, and planetary satellites. The gravitational forces these objects exert on nearby spacecraft are relatively small, allowing consideration of a hovering spacecraft trajectory as opposed to a more conventional orbital trajectory. For a hovering control law to be a viable mission option, a spacecraft under this control must be shown to have a stable trajectory and remain close enough to the desired hovering point to fulfill mission objectives. We have developed a detailed numerical simulation that allows us to evaluate various hovering control laws over arbitrarily shaped small-bodies.

0820 AAS 03-159

Development of Spacecraft Orbit Determination and Navigation Using Solar Doppler Shift
Troy A. Henderson, Andrew J. Sinclair, John E. Hurtado, and John L. Junkins; Texas A&M University

In using the Sun as a navigation reference body, we can obtain autonomous (self-contained) spacecraft navigation anywhere that the Sun is the dominant visible body. With this completely self-contained system, there is no need for ground support and the spacecraft can guide itself to anywhere in the solar system. We will discuss the utility of solar radial velocity knowledge to perform spacecraft orbit determination. The current state of our hardware to perform the measurements and the orbit determination algorithm will be discussed in detail, as well as future research plans.

0840 AAS 03-162

A Low Cost Pseudo-Galileo System for Civil Aircraft
Jianping Yuan and Xingang Li; Northwestern Polytechnical University, P. R. China

Galileo is an independent civil satellite navigation system which is now being developed. But for civil aviation there still have some issues to use this system. Here we presented a low cost Pseudo-Galileo system which consists of a high altitude navigation platforms stations system (HANPSS) network and the ground positioning station network. In this paper, the detailed description about Pseudo-Galileo is presented, including the system network structure, the signal format, the positioning method and the geometric performance analysis. Finally some simulation results are given to validate the feasibility and evaluate the performance of the regional positioning system.

0900 AAS 03-163

Multibody Parachute Flight Simulations for Planetary Entry Trajectories Using "Equilibrium Points"

Ben Raiszadeh, NASA Langley Research Center

A method has been developed that reduces numerical stiffness and computer CPU requirements of high fidelity multibody flight simulations involving parachutes for planetary entry trajectories. Typical parachute entry configurations consist of bodies suspended from a parachute, connected by flexible lines. To accurately calculate line forces and moments, the simulations need to keep track of the point where the flexible lines meet (confluence point). In previous multibody parachute flight simulations, the confluence point has been modeled as a point mass. Using a point mass for the confluence point tends to make the simulation numerically stiff, because its mass is typically much less that than the main rigid body masses. This forces the simulation to use a very small integration time step. In the method described in the paper, the need for using a mass as the confluence point has been eliminated. Instead, the confluence point is modeled using an "equilibrium point". This point is calculated at every integration step in the simulations and is the point where sum of all line forces equals to zero (static equilibrium). The use of this "equilibrium point" has the advantage of both reducing the numerical stiffness of the simulations, and eliminating the dynamical motion associated with vibration of a lumped mass on a high-tension string.

Break **0920–0950**

0950 AAS 03-158

WITHDRAWN

1010 AAS 03-160

WITHDRAWN

1030 AAS 03-161

WITHDRAWN

Session 9: Orbit Determination

Chair: Paul Cefola
Massachusetts Institute of Technology

0800 AAS 03-164

Near Real-Time Estimation of Local Atmospheric Density
James R. Wright, Analytical Graphics, Inc.

The purpose for this paper is to present a new stochastic model for the near real time estimation of atmospheric density local to spacecraft position, simultaneously with the estimation of the orbit and other appropriate state parameters, and to demonstrate its use with real LEO tracking data. By near real-time I refer to the lag required to calculate and present an optimal sequential state estimate from a real time measurement. For many applications this time lag is less than one second on computer equipment with modest CPU capability.The new stochastic model consists of a baseline near real-time atmospheric density error model appropriate for solar minimum and benign atmospheric conditions, and an integrated composit dynamic atmospheric density error model to accomodate impulsive atmospheric density events in near real-time during solar maximum.

0820 AAS 03-165

Comparison of MSIS and Jacchia Atmospheric Density Models For Orbit Determination And Propagation
K. Akins, Pennsylvania State University; L. Healy, S. Coffey, M. Picone, Naval Research Laboratory

Two atmospheric density model families that are commonly choosen for orbit determination and propagation, Jacchia and MSIS, are compared for accuracy. The Jacchia 70 model, the MSISE-90 model, and the NRLMSISE-00 model may each be used to determine orbits over fitspans of several days and then to propagate forward. With observations kept over the propagation period, residuals may be computed and the accuracy of each model evaluated. We have performed this analysis for over 4000 catalogued satellites with perigee below 1000km for October 1999, and the 60 HASDM calibration satellites with a large observation set for February 2001.

0840 AAS 03-166

Implementing the MSIS Atmospheric Density Model in OCEAN
Lisa A. Policastri and Joseph M. Simons; US Naval Research Laboratory

NRL uses the software package OCEAN for orbit determination and propagation. A new MSIS-class atmospheric density model, NRLMSISE-00, includes several notable differences from earlier atmosphere models, and has been added as an additional option in the OCEAN software. To date, two low-to-mid altitude satellites have been used to test this model. In every instance of testing, when comparing the RMS error of the differential correction, the MSIS model produced better results than OCEAN's Jacchia-1970 model. More LEO satellites have been selected as future test cases to determine the model's consistency.

0900 AAS 03-167

Determination of Atmospheric Density from the HASDM Data Set to Validate Density Extracted from UV Spectra

S. H. Knowles, Raytheon; A. Nicholas, J. M. Picone, and S. Thonnard, Naval Research Laboratory

Observations from the HASDM data set have been used to validate atmospheric density extraction from LORAAS UV spectra over the period 15 Jan to 28 Feb 2001. The analysis used values of satellite B terms determined from special perturbations orbit fits to generate drag-derived density corrections to compare with UV determinations.

Break **0920–0950**

0950 AAS 03-168

Preliminary Validation Of Atmospheric Neutral Density Derived From Ultraviolet Airglow Observations

S. E. Thonnard, A. C. Nicholas, J. M. Picone, K. F. Dymond, S. A. Budzien, Naval Research Laboratory; S. H. Knowles, Raytheon Technical Corp.; E. E. Henderlight, Praxis Inc.; R. P. McCoy, Office of Naval Research

Climatological atmospheric density models used for orbit determination and prediction have errors that range from 10% to 15%. For Low Earth Orbiting (LEO) satellites, the error due to an imprecise density specification is the most significant contribution to the error ellipse associated with the position of the object. This paper presents ultraviolet airglow derived atmospheric density corrections for the NRLMSISE-90 model during January and February 2001. Preliminary validation of the improved density specification is provided through comparisons to existing climatological models, a data driven atmospheric model and total density derived from satellite drag.

1010 AAS 03-169

Brightness Loss Of GPS Block II And IIA Satellites On Orbit

Frederick J. Vrba, U. S. Naval Observatory; Henry F. Fliegel, and Lori F. Warner, The Aerospace Corporation

We present results from an on-going groundbased multi-band photometric monitoring program of GPS block II and IIA satellites, from the U.S. Naval Observatory, Flagstaff Station. Our results show generally well-behaved lightcurves as a function of Sun-Observer-SV phase angle. Observations of satellites with a range of on orbit time of about ten years shows loss of surface reflectivity between 450-790 nm of about 10 percent/year. We discuss implications of how this might relate to solar panel power loss on these spacecraft. We also present early results for block IIR spacecraft and plans for future work.

1030 AAS 03-170

WITHDRAWN

1050 AAS 03-171

Comparison Of Accuracy Assessment Techniques For Numerical Integration

Matthew Berry and Liam Healy; Naval Research Laboratory

Knowledge of accuracy of numerical is important for composing an overall numerical error budget; in orbit determination and propagation for space surveillance, there is frequently a computation time-accuracy tradeoff that must be balanced. There are several methods to assess the accuracy of a numerical integrator. In this paper we compare some of those methods: comparison of the integration under test with two-body results, with forward-backward integration, with step-size halving, with a higher-order integrator, and with nearby exactly integrable solution. Selection of different kinds of orbits for testing is important, and an RMS error ratio may be constructed to condense results into a compact form.

Session 10: Space-Based Interferometry

Chair: David Hyland
University of Michigan

1330 AAS 03-172

Formation Motion and Control for Imaging Applications
I. I. Hussein, D. J. Scheeres and D. C. Hyland; University of Michigan

This paper states the basic relationships between the motion of an imaging constellation and imaging objectives. This leads to the formulation of a class of motions that satisfy imaging objectives and simple maneuvers to enforce these motions. Results indicate a tradeoff between image quality and fuel expenditure for the proposed class of maneuvers.

1350 AAS 03-173

Worst Case and Mean Squared Performance of Imaging Systems: A Feature-Based Approach
S. Chakravorty, P. T. Kabamba, and D. C. Hyland; University of Michigan

In this paper, we quantify the effect of random noise on the probability of misclassification of images. We consider two metrics for the noise corrupting the image: the mean squared error (MSE) and the worst case error (WCE). We show that these are consistent with the goal of image classification in that, as the MSE or WCE tends to zero, the probability of misclassifying an image also tends to zero. Given a feature map, i.e., a real-valued function of an image variable, we assume that classification is done by applying a threshold to the feature map. In this feature-based classification, we find bounds on the MSE and the WCE such that the probability of misclassifying the image is guaranteed to be less than some pre-specified value. We illustrate the theory through an example where the banded appearance of the image of a planet is detected. We also show that, in the special case of a linear feature map, finding an estimate that minimizes the probability of misclassification reduces to a problem of finding a minimum weighted-MSE estimate. The results of this paper could be used for the reliable characterization of exo-solar planets and similar astronomical studies.

1410 AAS 03-174

Interferometric Observatories in Low Earth Orbit
I. I. Hussein, D. J. Scheeres and D. C. Hyland; University of Michigan

This paper proposes a class of satellite constellations that can act as interferometric observatories in Low Earth Orbit, capable of forming high resolution images in time scales

of a few hours without the need for active control. The practical implementation of these observatories is discussed.

1430 AAS 03-175

Design of Spacecraft Formation Orbits Relative to a Stabilized Trajectory
F. Y. Hsiao and D. J. Scheeres, University of Michigan

This paper investigates the design of spacecraft formation orbits traveling relative to a general trajectory. To describe the motion we approximate the time-varying linear dynamics about the trajectory with a locally time-invariant system and use linear orbit elements to describe the relative trajectories. We find sufficient conditions under which the relative motion is stable and a controller can be designed. We consider the problem of specifying the orientation of the fundamental orbits, which is equivalent to eigenvector placement, and show how these modes can be combined to force the formation to fly in a range of orientations. Applications of our approach to relative motion in rotating and non-rotating systems are given.

Break **1450–1520**

1520 AAS 03-176

Optimal Coordination in Formation Flight: Rendezvous and Breakup
V. G. Rao and P. T. Kabamba, University of Michigan

This paper poses and provides solutions for a class of simplified coordinated-motion problems, along with proofs of optimality. Anexhaustive characterization of the behavior of the optimal solutions,including conditions governing rendezvous and formation breakup, is alsoprovided. The results are applied to a transatlantic flight example, andfuel savings of the order of 4% are shown to be plausible.

1540 AAS 03-177

Probabilistic Controller Analysis and Synthesis for Quadratic Performance: The Method of HPD Inscription
Hiroaki Fukuzawa and Pierre T. Kabamba; University of Michigan

Probabilistic control of linear time-invariant and linear periodic systems is considered. Here the plant is subject to uncertainty such that the uncertain plant parameters are jointly Gaussian. The HPD inscription method utilizes the fact that stability and performance impose linear constraints on the eigenvalues of the solution of a Lyapunov equation. Results are presented for control analysis and synthesis. These results are illustrated on a simple example of control of an uncertain orbit.

Session 11: Constellations

Chair: Michael Zedd
Naval Research Laboratory

1330 AAS 03-178

Walker Constellations to Minimize Revisit Time in Low Earth Orbit
Thomas J. Lang, The Aerospace Corporation

In the design of satellite constellations, continuous coverage of the region of interest is not always necessary. By allowing viewing gaps or revisit times, it may still be possible to meet mission objectives while substantially reducing the required number of satellites. In this study, a brute force technique is employed to find the best symmetric, Walker type constellation (including inclination) that minimizes the global maximum revisit time (MRT) for numbers of satellites between 3 and 40. A parametric approach is used to cover the LEO regime from 700 to 1500 km in altitude and for minimum elevation angles from 0 to 20 degrees.

1350 AAS 03-179

Daily Repeat-Groundtrack Mars Orbits
Gary K. Noreen, Roger E. Diehl, Stuart J. Kerridge, Tomas A. Komarek, Todd A. Ely, Andrew E. Turner, Joseph G. Neelon; Jet Propulsion Laboratory

The G. Marconi Orbiter (GMO) will be placed into a Mars orbit designed to optimize relay support to in-situ Mars probes. Relay users, such as rovers or small landers on the surface of Mars, would like GMO to be in a daily repeat-groundtrack orbit so that they can design their missions and their operations based on invariant contact times. This paper identifies 42 Mars orbits with repeat ground tracks and compares the relay performance of some of these orbits based on coverage area, connectivity and data volume.

1410 AAS 03-180

Single Satellite Orbital Figure-of-Merit
John E. Draim, USN ret.; John L. Young III and David Carter, Draper Laboratory; Paul J. Cefola, Massachusetts Institute of Technology

A metric that can be used by satellite designers to compare the cost-effectiveness of different orbits would be a valuable way to determine the optimal orbit for a single satellite and by extension, a constellation of satellites. This paper investigates the properties of a new figure-of-merit for single-satellite orbits proposed by Draim: the ratio of coverage to required launch delta v.

1430 AAS 03-181

Analysis of Small Constellations of Satellites for Mid-Course Tracking
Irene A. Budianto, Daniel Gerencser, and Patrick J. McDaniel; USAF Research Laboratory

A methodology employing genetic algorithm was developed to design a small constellation of satellites to track a missile during the mid-course phase of its flight. The objective was for the space-based system to provide a single intercept of the target trajectory that can be handed over to other defensive elements. Therefore, continuous coverage of the moving point is not required. The solution to this problem is highly dependent on the specific target trajectory considered. For the chosen test scenario, as few as two satellites were able to accomplish the objective, resulting in an acceptable maximum gap and percent coverage.

Break **1450–1520**

1520 AAS 03-182

Drag and Stability of a Low Perigee Satellite
Mark J. Lewis and Joseph R. Schultz; University of Maryland

This paper will present an analysis of the aerodynamic performance of the GEC constellation spacecraft, designed to enter the earth's atmosphere in a series of low-perigee orbits. Drag, lift, and aerodynamic moments are calculated at perigee, with a focus on energy loss through each atmosphere pass. Rarefied aerodynamic models are applied to the determination of force contributions from all surfaces of the spacecraft including magnetometer booms. Issues related to drag reduction, maximizing solar cell surface area, and packaging volumetrics will be discussed. The effect of drag differences between constellation elements will also be highlighted, as will the stabilizing, or destabilizing effect of aerodynamic moments. Finally, suggestions for improved geometries which reduce drag and improve stability will be presented.

1540 AAS 03-183

A New Satellite Constellation Augment System—Space Station Utilisation
Qun Fang, Lvping Li, Zhiwei Du, and Dou Xiaomu; Northwestern Polytechnical University, Xi'an, China

This paper analyzes the advantages and disadvantages of space station and constellation and presents a new scheme that space station is integrated with the satellite constellation and regarded as a administrator in the augment system. Method about the communication links between space station and constellation are discussed. Finally simulation results about the integrated augment system (international space station (ISS) integrated with Delta constellation) was given in the end.

Session 12: Orbital Debris

Chair: David Spencer
Pennsylvania State University

1330 AAS 03-184

Improved Analytical Expressions For Computing Spacecraft Collision Probabilities
Ken Chan, The Aerospace Corporation

This paper presents an improved analytical expression for computing the collision probability between two orbiting objects. In the encounter plane, a scale transformation converts the bivariate Gaussian probability density function (pdf) to an isotropic Gaussian pdf and the circular cross-section to an elliptical one. By approximating this elliptical with an equivalent circular cross-section, the two dimensional Gaussian distribution is replaced by a one dimensional Rician, the integral of which is known in the form of a convergent infinite series. Typical examples show that the error bound for truncation after the first term appears in the third or fourth significant digit. Comparisons have been made with other methods involving numerical evaluation of the collision integral. Agreement is observed for at least three significant figures for extremely close encounters with collision probabilities of 1e-1 to distant encounters with probabilities of 1e-28.

1350 AAS 03-185

Risk Of Collision For The Navigation Constellations: The Case Of The Forthcoming GALILEO
A. Rossi, ISTI-CNR; G. B. Valsecchi, IASFC-CNR; E. Perozzi, Telespazio S.P.A.

The European navigation constellation Galileo will orbit the Medium Earth Orbit (MEO) region close to the GPS and the GLONASS systems. Beyond the constellation related spacecraft, more than 20 000 objects larger than 1 cm have orbits possibly interacting with the constellations. An impact between an operational satellite and a debris (either a fragment or an abandoned spacecraft) cannot be ruled out. An assesment of the collision risk for the next decades between the spacecraft of the three constellations and the evolved debris population is performed, exploiting the method developed by Valsecchi et al. (Nature, 1999), based on Opik's studies. Then the collision risk between the multiplane constellations and a cloud of debris following the fragmentation of a spacecraft in the MEO region will be assessed. For this purpose the Opik's theory is extended to be more suited to the MEO dynamical environment where the random orientation of the angular arguments cannot be granted.

1410 AAS 03-186

The 2002 Italian Optical Observations of the Geosynchronous Region

Manfredi Porfilio, Fabrizio Piergentili, Filippo Graziani; University of Rome "La Sapienza", Italy

In the April 2002 the first dedicated observations of space debris in Italy have been performed by the Group of Astrodynamics of the University of Rome "La Sapienza". The campaign was accomplished using one of the Campo Catino Astronomical Observatory telescopes: a 25 cm Baker-Schmidt coupled with a 1024'1024 back-illuminated CCD sensor; the target was the geosynchronous region. As the test observations were successful, other campaigns have been scheduled. In the paper are reported the results of the whole 2002 GEO observations from Campo Catino.

1430 AAS 03-187

A Geometrical Approach To Determine Blackout Windows At Launch

Vincent Rabaud and Béatrice Deguine; Ecole Nationale Supérieure de l'Aéronautique et de l'Espace, Toulouse, FRANCE

Determining the blackout launch window is a combinatory problem using a large amount of data. As there are many possible cases, we have been looking for a new and general method which can give results in a few minutes. In order to demonstrate the feasibility and the efficiency of our approach, we first consider the debris as Keplerian. The method uses several basic geometrical tests to determine when and where a debris gets into a volume based upon a one sheeted hyperboloid. To be more accurate, some perturbations are then applied to the debris trajectories. Some results and benchmark will also be given.

Break **1450–1520**

1520 AAS 03-188

Orbital Debris Analysis of TIMED Spacecraft Mission

Surjit Badesha, Applied Physics Laboratory; S. K. Dion, Goddard Space Flight Center; R. E. O'Hara, Lockheed Martin Space Operations

This paper describes the TIMED spacecraft hardware, operational scenarios, and orbital debris analysis, along with the assumptions and results. The analysis was done using NASA's Debris Assessment Software (DAS) program. The DAS predicted the area-time product exceeds the requirement limit of 0.1 m^2-yr close to the potential 650 km altitude. However, an orbital decay program that uses 50th percentile real time solar flux values in the predicts a significantly lower orbital lifetime in compliance with NSS 1740.14. Additionally, the total debris casualty area of 9.2 m^2 slightly exceeded the guideline requirement value of 8 m^2. Reanalysis of the reentry survivability, using NASA's enhanced DAS code Object Reentry Survival Analysis Tool (ORSAT), resulted in a significantly lower value of 5.2 m^2 in compliance with NSS 1740.14.

1540 AAS 03-189

WITHDRAWN

Session 13: Attitude Determination and Dynamics

Chair: Beny Neta
Naval Postgraduate School

0800 AAS 03-190

Conformal Mapping among Orthogonal, Symmetric, and Skew-Symmetric Matrices
Daniele Mortari, Texas A&M University

Cayley Transforms are a beautiful and useful math tool to perform one-to-one Orthogonal/ Skew-Symmetric matrix mapping. Applications can be found in dynamics, control, and in applied representation theory. The paper shows that Cayley Transforms represent the extension to matrix field of the $f_1(z)$ complex conformal function. Then it shows that two other functions [namely, $f_2(z)$ and $f_3(z)$], here called clockwise and counter clockwise, can also be extended to matrix field to perform the Orthogonal/Symmetric and the Symmetric/Skew-Symmetric matrix mapping, respectively. This completes the mapping for these three most used matrices. Finally, another general method allowing the complete Orthogonal/Symmetric/Skew-Symmetric matrix mapping, is introduced.

0820 AAS 03-191

Spacecraft Angular Rate Estimation Algorithms For A Star Tracker Mission
Puneet Singla, John L. Crassidis, and John L. Junkins; Texas A&M U., College Station

In this paper, two different algorithms are presented for the estimation of spacecraft body angular rates in the absence of gyro rate data for a star tracker mission. In first approach, body angular rates are estimated with the spacecraft attitude using a dynamical model of the spacecraft. Second approach makes use of rapid update rate of star camera to estimate the spacecraft body angular rates independent of spacecraft attitude. The relative merits of both the algorithms are then studied for the spacecraft body angular rates measurements. Second approach has got an advantage of being free from any bias in attitude estimates.

0840 AAS 03-192

Autonomous Artificial Neural Network Star Tracker for Spacecraft Attitude Determination
Aaron J. Trask and Victoria L. Coverstone; University of Illinois at Urbana-Champaign

An artificial neural network based autonomous star tracker prototype for precise spacecraft attitude determination is developed. Night sky testing is used to validate a system consisting of a charged-coupled-device-based camera head unit and integrated control hardware and software. The artificial neural network star pattern match algorithm utilizes a sub catalog of the SKY2000 star catalog. The experimental results are real time comparisons of the star tracker observed motion with the rotational motion of the Earth.

0900 AAS 03-193

Attitude Determination Algorithm For Gyroless Spacecraft Using Disturbance Accommodation Technique

Injung Kim, Seoul National University, Jinho Kim, Swales Aerospace; Youdan Kim, Seoul National University

Several attitude determination algorithms for a gyroless spacecraft have been proposed for the last few decades. In this paper, we propose a new approach to estimate the attitude and rate of this spacecraft. Generally, we can guess that the true attitude dynamics consists of the known reference model and the unknown residual dynamics. Then, disturbance accommodation technique can be utilized to estimate this unknown term. This technique estimates the residual dynamics model approximated as a linear combination of known basis functions. In this study, we use the power set of time and sinusoidal functions as a basis function. Finally, application examples for ACDS and conclusive discussion are given.

Break **0920–0950**

0950 AAS 03-194

Singularity of the Covariance Matrix and Quaternion Normalization in Attitude Determination Filters

Mark E. Pittelkau, Applied Physics Laboratory

The full-quaternion attitude determination filter is analyzed to address questions of covariance singularity and quaternion normalization. It is shown how nonsingularity of the covariance in the Extended Kalman Filter depends on the initial covariance, the process noise matrix, and implementation details of the filter. The covariance of a normalized quaternion estimate and the various means to achieve normalization are examined. The effect of a quaternion measurement update on the covariance and on the norm of the estimated quaternion is analyzed. It is also shown that the multiplicative and additive quaternion updates are equivalent. These are distinguished from an update called "rotational", which was proven elsewhere to be the constrained maximum-likelihood optimal update. It is demonstrated that the reduced-order body-referenced attitude determination filter is embedded in the full-quaternion filter.

1010 AAS 03-197

Attitude Interpolation

Sergei Tanygin, Analytical Graphics, Inc.

Attitude and orbit ephemeris interpolations provide means for computing attitude and ephemeris at times not included in the original data set, whether simulated or real. They are typically performed for one of two reasons: as an alternative to numerical integration in the absence of force modeling information or as a way to speed up computations. Compared to ephemeris, attitude interpolation offers some additional challenges due to inherent properties of attitude parameterizations, e.g. singularities of 3-dimensional parameterizations, additional constraints of 4-dimensional parameterizations and aliasing of different revolutions for spinning trajectories. This paper presents both Lagrange and Hermite formulations for attitude interpolation, evaluates their performance and investigates their use for design of commanded slews.

1030 AAS 03-195

WITHDRAWN

1050 AAS 03-196

WITHDRAWN

Session 14: Navigation and Orbit Determination-Operations-I

Chair: Kim Luu
US Air Force Research Laboratory

0800 AAS 03-198

Reconstruction of the Voyager Saturn Encounter Orbits in the ICRF System
R. A. Jacobson, JPL/Caltech

The Voyager 1 and Voyager 2 spacecraft visited the Saturnian system in November 1980 and August 1981, respectively. Campbell et al. (AIAA Paper 82-0419) discussed the determination of the spacecraft orbits. Campbell and Anderson (1989 AJ 97, 1485) used data from the encounters to improve knowl- edge of the Saturnian gravity field. In anticipation of the Cassini tour, we have re-examined the results from the Voyager mission. We obtain Voyager trajec- tories in the International Celestial Reference Frame, and we revise the gravity field taking advantage of improvements made in modelling and data processing since the previous work. We also incorporate a full dynamical model for the Saturnian satellites into the analysis for the first time.

0820 AAS 03-199

Satellite Ephemerides Update Schedule for the Cassini Mission
Ian Roundhill and Duane Roth; Jet Propulsion Laboratory

The Cassini mission will arrive at Saturn in July 2004 to explore the Saturnian system including the satellites. The navigation team will update the ephemerides of 9 of these satellites to improve spacecraft navigation and provide information on satellite location for pointing of the spacecraft. This paper outlines the approach used to predict pointing uncertainty when pointing information is generated with a spacecraft prediction and older satellite ephemerides. This modeling is then used to choose times when the satellite ephemerides need to be updated to meet requirements.

0840 AAS 03-200

Cassini Navigation During Solar Conjunctions Via Removal Of Solar Plasma Noise
P. Tortora, L. Iess, Università di Roma ”la Sapienza”, Italy; J. J. Bordi, J. E. Ekelund, D. Roth, Jet Propulsion Laboratory

The Cassini spacecraft and its ground segment are currently used to test a novel RF multilink technology to perform radio science experiments. During solar conjunctions, this allows the complete removal of the solar plasma noise from the navigation observables, coherently combining the signals received in the three bands X/X, X/Ka and Ka/Ka. During the June-July 2002 Cassini solar conjunction, this procedure was tested for the first time. We show that, using the multifrequency plasma calibration scheme, the rms value of the frequency residuals is reduced of a fact or of 200 over the uncalibrated data.

0900 AAS 03-201

Interplanetary Navigation During ESA's BepiColombo Mission to Mercury

R. Jehn, ESA/ESOC, Germany; J. L. Cano, Spain, DEIMOS Space S.L.; C. Corral, GMV S.A., Germany, M. Belló-Mora, DEIMOS Space S.L., Spain

The BepiColombo interplanetary trajectory combines low-thrust arcs with gravity assists. Especially the low flybys over Venus and Mercury and the final insertion into a Mercury orbit pose challenging navigation requirements. The navigation based on a low-thrust propulsion system is the subject of the present paper. This includes the assessment of the orbit determination accuracy during coast and thrust arcs as well as the performance of the propulsion system and the ranging devices. The improvements due to the use of advanced measuring techniques like Delta-DOR are investigated. The paper also addresses the guidance problem, where the flyby points in the impact plane have to be reached with high accuracy. Whether the solar-electric propulsion system is suitable to navigate the BepiColombo spacecraft with the required accuracy to the flyby targets and how it can be done is presented.

Break **0920–0950**

0950 AAS 03-202

Genesis Trajectory And Maneuver Design Strategies During Early Flight

Roby S. Wilson and Kenneth E. Williams; Jet Propulsion Laboratory

As the fifth Discovery mission, the Genesis spacecraft was launched on August 8, 2001 with a science objective to collect solar wind samples for a period of approximately two and a half years while in orbit in the vicinity of the Sun-Earth L1 Libration point. These samples will eventually be delivered back to the Earth for analysis, posing a formidable challenge in terms of both mission design and navigation. This paper discusses trajectory and maneuver design strategies employed during the early phases of flight to accommodate spacecraft and instrument design constraints, while achieving the science objectives of the mission. Topics to be discussed include: mission overview, spacecraft design and constraints, maneuver analyses and trajectory re-optimization studies, and operational flight experience to date.

1010 AAS 03-203

Orbit Determination Support for the Microwave Anisotropy Probe (MAP)

Son H. Truong, Osvaldo O. Cuevas, NASA Goddard Space Flight Center; Steven Slojkowski, Computer Sciences Corporation, Lanham-Seabrook, Maryland

NASA's Microwave Anisotropy Probe (MAP) was launched on June 30, 2001. MAP used a lunar swingby stratety to achieve a lissajous orbit about the Earth-Sun L2 Lagrange point. The mission provided a unique challenge for orbit determination (OD) support in many orbital regimes. This paper summarizes the premission covariance analysis and actual OD results. There will be a discussion of the challenges presented to OD support including the effects of delta-Vs, and the impact of the spacecraft attitude mode on the OD accuracy and covariance analysis. Important lessons learned from the MAP OD support team will be presented.

1030 AAS 03-204

Navigating CONTOUR Using the Noncoherent Transceiver Technique
Eric Carranza, Anthony H. Taylor, Bobby G. Williams, George D. Lewis, Dongsuk Han, Cliff E. Helfrich, Ramachand Bhat, Jamin S. Greenbaum, J. Robert Jensen, Karl Fielhauer, Jet Propulsion Laboratory

Navigation of the Comet Nucleus Tour (CONTOUR) spacecraft was performed at the Jet Propulsion Laboratory and was conducted with the use of the new noncoherent transceiver technique developed by the Applied Physics Laboratory. A description of the mission and its trajectory will be provided, followed by a discussion of the data conditioning performed on the 2-way noncoherent Doppler data, as well as a discussion of the orbit determination estimation procedure, models and accuracies. The orbit determination was performed using X-band 1-way, corrected 2-way noncoherent Doppler data and 2-way noncoherent SRA range data, collected primarily by the DSN 34m network.

1050 AAS 03-205

Estimating General Relativity Parameters from Radiometric Tracking of a Heliocentric Trajectory
R. S. Park, D. J. Scheeres, University of Michigan; G. Giampieri, Blackett Laboratory Imperial College, London, UK; J. M. Longuski, and E. Fischbach, Purdue University

The theory of General Relativity can be tested by precisely measuring small changes in the trajectory of a spacecraft as it escapes from the Sun on a hyperbolic orbit. An important question is with what accuracy the relativistic coeffcients gamma and beta can be estimated from such a trajectory. In this paper we present a detailed covariance analysis of this question, analyzing uncertainties in the spacecraft state and in the general relativity parameters. Three different measurement data types are simulated in our analysis, range, Very Long Baseline Interferometry (VLBI), and Doppler. Also included are the effects of different phase angles between the Earth and the spacecraft trajectory. The worst case analysis shows that estimates of these parameters should be obtainable to the order of 0.001 or better, assuming relatively modest improvement in measurement capabilities.

Session 15: Mission Design-I

Chair: Dennis Byrnes
Jet Propulsion Laboratory

0800 AAS 03-206

Aqua Maneuvers During the 120-Day Checkout Period
Peter Demarest, Susan Good, David Rand, Clint Stone, Tim Velegol; a.i. solutions Inc.

On May 4, 2002 at 04:54 EST NASA's Aqua spacecraft was launched from Vandenburg AFB aboard a Delta II rocket. After separation from the launch vehicle, a series of ascent maneuvers were performed to raise the spacecraft into its operational orbit. During the first 120 days of the mission two calibration burns, six ascent burns, and two ground track maintenance maneuvers were performed under the supervision of the Aqua Flight Dynamics Systems Team. These maneuvers successfully placed Aqua in a frozen, sun-synchronous orbit, centered on the WRS-2 grid and phased relative to the Terra spacecraft. Completion of these maneuvers prepared the flight dynamics system and spacecraft for routine maneuver operations, to be conducted by the Aqua Flight Operations Team.

0820 AAS 03-207

SIRTF Mission Design
Eugene P. Bonfiglio and Mark Garcia, Jet Propulsion Laboratory

The Space Infrared Telescope Facility (SIRTF) was most recently scheduled to launch on July 15, 20021. Due to project delays, SIRTF is now slated to launch on January 9, 2003. Using a Delta 7920H launch vehicle and a direct ascent trajectory, SIRTF will launch into an Earth-trailing solar orbit at which point it will begin a 2.5 to 5 year mission. During its mission, SIRTF will be performing some of the best infrared astronomy to date. This paper presents the latest trajectory data, injection dispersion analysis performed to guarantee SIRTF will be injected into an acceptable orbit (SIRTF has no onboard propellant for trajectory correction), asteroid searches, and other new topics relating to the SIRTF mission design.

0840 AAS 03-208

Design and Implementation of CONTOUR's Phasing Orbits
David W. Dunham, Daniel P. Muhonen, Robert W. Farquhar, Mark Holdridge, Edward Reynolds, Applied Physics Laboratory

The CONTOUR (COmet Nucleus TOUR) spacecraft was launched on July 3, 2003 into Earth phasing orbits. This paper will describe the successful maneuvers performed during

43 days in these orbits to accurately achieve the time, state vector, and spacecraft attitude and mass needed for a solid rocket motor (SRM) burn that inserted CONTOUR into a heliocentric orbit intended to use Earth swingbys with 1-year returns to fly close to at least two comets. Operations were virtually perfect until a mishap near the end of the SRM burn apparently destroyed the spacecraft.

0900 AAS 03-209

MESSENGER Mercury Orbit Trajectory Design
James V. McAdams, Applied Physics Laboratory

MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) will be the first spacecraft to orbit the planet Mercury when this NASA Discovery Program mission begins its one-year Mercury orbit phase in April 2009. The spacecraft's thruster locations, sunshade orientation constraints, and a requirement that all maneuvers be observable from Earth are factored into the design of the Mercury orbit-insertion maneuver and all six subsequent planned orbit-correction maneuvers. This paper will explore trajectory perturbation effects of solar radiation pressure on a variable Sun-relative spacecraft attitude, as well as recovery options for delayed maneuvers.

Break **0920–0950**

0950 AAS 03-210

Options For A Mission To Pluto And Beyond
Massimiliano Vasile, Andres Galvez, Leopold Summerer, Robin Biesbroek, Gerhard Kminek; European Space Technology Centre (ESA/ESTEC), The Netherlands

No spacecraft has ever visited Pluto, however there is unanimity on the scientific interest of the Pluto-Charon system and that of the Kuiper Belt Objects. In this paper optimised trajectories toward the limit of the solar system with innovative propulsion systems as well as with more traditional chemical propulsion are investigated and a preliminary assessment of a combined mission to Pluto and to a closer system with a composite spacecraft is performed. Non-chemical trajectories are designed with a direct method and a global optimisation strategy to procure sets of promising initial guesses. Orbits using no thrust arcs or impulsive shots are assessed by means of 'C3 matching' and enumerative search. Some alternatives using aero-gravity assists are also shown.

1010 AAS 03-211

Trajectory Design for the Mars Reconnaissance Orbiter Mission
C. Allen Halsell, Angela L. Bowes, Daniel T. Lyons, M. Daniel Johnston, Robert E. Lock, Peter Xaypraseuth, Shyam Bhaskaran, Dolan E. Highsmith, Moriba K. Jah; Jet Propulsion Laboratory

This paper describes the analysis and design evolution of the Mars Reconnaissance Orbiter trajectory from launch to end-of-mission. The mission uses a combination of propulsive maneuvers and aerobraking techniques to deliver the orbiter to a low-altitude frozen orbit at Mars. The launch/arrival space for the 2005 Earth-Mars opportunity will be described as well as the particular launch strategy chosen for this mission. Details of the aerobraking profile will be provided. Finally, the Primary Science Orbit will be examined, and the trade-offs between science objectives and orbiter capability will be presented.

1030 AAS 03-212

Primary Science Orbit Design for the Mars Reconnaissance Orbiter Mission
Angela L. Bowes, C. Allen Halsell, M. Daniel Johnston, Robert E. Lock, Peter Xaypraseuth, Daniel T. Lyons, Shyam Bhaskaran, Dolan E. Highsmith; Jet Propulsion Laboratory

This paper addresses the constraints, analysis, and design evolution of the Mars Reconnaissance Orbiter Primary Science Orbit. The discussion details the tradeoffs made to satisfy science objectives within the capability of the spacecraft and mission cost. Science objectives and the corresponding requirements levied on the orbit mission design are presented. Atmospheric effects on both the orbit itself and the spacecraft are discussed in terms of their impact on the final PSO selection. The decision rationale for the final selection of the orbital altitude and frozen orbit is also presented.

1050 AAS 03-213

Flying Dynamics of the Lunar Probe and Its Orbit Design & Computation
Zhang Zhenmin, Harbin Institute of Technology, P.R. China

This paper investigates the precise designing and computing technology of the lunar probe orbit. First, the author establishes the motional differential equation of the lunar probe according to the theory and the method of spacecraft orbital dynamics; Then the flying orbit of the lunar probe is obtained by using the numerical integration method. The method used in this paper can provide reference for engineers and technicians in the future.

Session 16: Tethers

Chair: Chris Hall
Virginia Tech

1330 AAS 03-214

Libration Control Of Electrodynamic Tethers In Inclined Orbit
J. Pelaez, Universidad Politecnica de Madrid, Spain; E. C. Lorenzini, Smithsonian Astrophysical Observatory, Cambridge, MA

Electrodynamic tethers orbiting in inclined orbits are analyzed in the paper. These tethers are unstable in the absence of control or without damping. In the paper, two different kinds of control laws are analyzed: the first one is based on an unstable periodic orbit in the phase space which is taken as the reference orbit. The second one is based on an extended delay feedback mechanism that has been already tested in one degree of freedom systems and it is now extended to a two degrees of freedom system. In both cases the unstable periodic orbit becomes asymptotically stable.

1350 AAS 03-215

Damping In The Dynamic Stability Of Deorbiting Bare Tethers
J. Pelaez, Universidad Politécnica de Madrid, Spain; M. Lara, Real Observatorio de la Armada, Spain

Electrodynamic bare tethers used as deorbiting devices are analyzed in this paper. The long-tether regime will be considered in order to describe the electrodynamic torque acting on the tether. It depends on the tether attitude in the orbital frame, i.e., on the in-plane and the out-of-plane angles for a rigid tether. The goal is to analyze how damping affects the stability properties of electrodynamic bare tethers operated in a circular inclined orbit. Simple models will be assumed for the environment where the tether works.

1410 AAS 03-216

Modeling and Estimation of ProSEDS Decay
Mario L. Cosmo and Enrico C. Lorenzini, Harvard-Smithsonian Center for Astrophysics

Electrodynamic tethers using bare anodes are particularly appealing in space transportation because when compared to previous tether systems, they require shorter lengths and lighter tethers for similar currents. This new transportation technology will be demonstrated in early 2003 when the Propulsive Small Expendable Deployer System (ProSEDS) will de-orbit a Delta second stage by using electrodynamic forces while recharging the

onboard batteries for operations. The high complexity of ProSEDS dynamics needs sophisticated numerical tools to model the orbital behavior and the current distribution along the tether. The aim of the paper is to present the tools developed to model and predict ProSEDS decay.

1430 AAS 03-217

Dynamics Of Bead-Models For Tethered Systems Under Perturbed Motion
Robin Biesbroek, JAQAR Space Engineering, The Netherlands; Ean Crellin, ESA/ESTEC mathematical Studies Office, The Netherlands

In this paper it is shown how accurate simulations of space tethers under perturbed motion can be performed in short time. The innovation in this model is the combination of many relatively simple equations of motion forming a fast system capable of simulating very complex motion. The tether in space is modelled as a set of point masses (beads) connected by straight, inextensible and mass-less lines. The equations for all perturbations are derived and shown, and some examples are given. Comparison between this model and sophisticated continuous models have shown very good agreement. In addition, the integration times of the bead model described in this paper were found to be very short.

Break **1450–1520**

1520 AAS 03-218

Dynamics of a Multi-Tethered Satellite System Near the Sun-Earth Lagrangian Point
A. Misra and B. Wong; Mcgill University, Canada

This paper will examine the dynamics of a tether connected multi-spacecraft system, arranged in a wheel-spoke configuration, in the vicinity of or in a halo orbit around the L2 Lagrangian point of the Sun-Earth system. Equilibrium configurations of the system are determined and small motions about these configurations are analyzed. An numerical analysis of the motion of the parent mass and tether libration is carried out for a four end-masses case when the system is near L2. Control effort required to maintain the tethered system's intended orbit and tether orientation would be determined.

1540 AAS 03-219

Flexibility Effects on Non-Planar Spin-Up Dynamics of Artificial-Gravity-Generating Tethered Satellite System
Andre P. Mazzoleni, Texas Christian University; John H. Hoffman, University of Texas

This paper concerns analysis of the non-planar spin-up dynamics of the Tethered Artificial Gravity (TAG) satellite. In the study of the dynamic motion of the TAG satellite, equations of motion for the system have been generated and integrated numerically. The analyses to be presented in this paper will account for the flexibility of the tether and will consider non-planar motion; an earlier study considered flexibility effects but assumed that the motion was constrained to the orbital plane.

1600 AAS 03-220

Control Of A Rotating Variable-Length Tethered System
M. Kim and C. D. Hall; Virginia Tech

We develop and illustrate techniques to control the motion of a Tethered Satellite System (TSS) comprised of n point masses and interconnected arbitrarily by m idealized tethers. In particular, the control problem of a triangular and symmetrical TSS with n = 3 point masses and m = 3 tethers is discussed. The equations of motion are derived using Lagrange's equations. Several mission scenarios for a proposed NASA mission considering the operation of an infrared telescope are introduced and asymptotic tracking laws based on input-state feedback linearization are developed. Required thrust levels can be significantly decreased by using additional tether length control.

1620 AAS 03-221

Retargeting Dynamics Of A Linear Tethered Interferometer
C. Bombardelli, University of Padova; E. C. Lorenzini, Harvard-Smithsonian Center for Astrophysics; M. B. Quadrelli, Jet Propulsion Laboratory

The paper deals with the issue of changing the plane of rotation (retargeting) of a linear kilometer-size formation of two collectors and one combiner spacecraft connected by two tether arms. A strategy is proposed that makes use of a pair of electrical thrusters located on board two of the three spacecraft to change the angular momentum of the formation and redirect it to a new target with an accuracy of better than 10 arc-s. The thruster profile is optimized to achieve an extremely smooth but relatively fast maneuver while minimizing the overall fuel consumption. A numerical model is employed to evaluate the effect of the thrust on the lateral dynamics of the tethers after the maneuver has been performed and in turn on the Optical Path Delay stability of the interferometer.

1640 AAS 03-222

Analysis and Damping of Lateral Vibrations in a Linear Tethered Interferometer
E. C. Lorenzini, Harvard-Smithsonian Center for Astrophysics; C. Bombardelli, University of Padova, Italy; M. B. Quadrelli, Jet Propulsion Laboratory

The vibration equations of a linear tethered interferometer spinning around its center of mass are derived. The system consists of two collectors and one combiner modeled as point masses and connected by two tether arms modeled as elastic continua. The equation of motions for small displacements are derived by means of a Lagrangian density function. The eigenvalue problem is solved analytically for the out-of-plane lateral oscillations, which are directly linked to the Optical Path Delay of the interferometer. A control strategy is presented for damping out these oscillations at the tether attachment point. This is demonstrated with a numerical model.

Session 17: Orbit Determination-II

Chair: Shannon Coffey
Naval Research Laboratory

1330 AAS 03-223

Autonomous Landmark Based Spacecraft Navigation System
Yang Cheng and James K. Miller; Jet Propulsion Laboratory

An autonomous landmark based spacecraft navigation scheme is presented. This new scheme involves the following data processing algorithms: Image selection and planning; Crater detection algorithm; Preliminary image matching; Crater match algorithm, Data base management; and Orbit determination filter. The system has been successfully tested on the 200 km NEAR orbit imagery. In the 200km orbit, 100 m accuracy was obtained after an hour of processing, which required several weeks of processing using manual crater detection and matching.

1350 AAS 03-224

Optical Landmark Detection and Matching for Spacecraft Navigation
Yang Cheng, Jet Propulsion Laboratory; Andrew E. Johnson, Jet Propulsion Laboratory; Clark F. Olson, University of Washington; Larry H. Matthies, Jet Propulsion Laboratory

This paper presents two key components of a crater-based autonomous navigation system: a crater detection algorithm and a crater matching algorithm. The crater detection algorithm can achieve sub-pixel accuracy in both crater position and geometry while its detection rate is better than 90% and its false alarm rate is less than 5%. The crater matching algorithm is able to determine spacecraft position by matching extracted image craters to a database containing craters. Both algorithms are ideal tools for autonomous landmark based spacecraft navigations.

1410 AAS 03-225

WITHDRAWN

1430 AAS 03-226

A Model for Satellite Position and Velocity with Respect to Ground Topography
Stefano Casotto, University of Padua, Italy

A typical instrumentation package in planetary observation missions is a radar altimeter or a lidar, which takes either range or velocity measurements of an electromagnetic pulse/signal reflected off the ground. For measurement system analysis or for experiment effectiveness/response analysis it may be of interest to have available an analytical model of the motion of the satellite with respect to the topography of the planet/minor body. It is the purpose of this paper to develop such model on the basis of a Kaula-type theory of satellite radial motion and a representation of the main body topography in spherical harmonics. This is achieved by introducing a representation of the elevation model along the ground-track of the satellite.

Break **1450–1520**

1520 AAS 03-227

Contributions of Individual Forces to Orbit Determination Accuracy
Justin E. Register, Naval Research Laboratory

The accuracy of orbit determination and prediction solutions depends heavily on the physical forces modeled. Although gravitational effects produce the largest perturbations, many other forces must be considered when accurate orbits are desired. This paper comprises two parts. First, the individual forces acting on satellites in various orbit regimes are tabulated and compared. Second, the contributions of individual forces to orbit determination accuracy are quantified. The forces considered are central body, J2, and higher order gravity harmonics, third-body gravity, drag, solar pressure, indirect lunar oblateness, solid and ocean tides, the so-called pole tide, and general relativistic effects.

1540 AAS 03-228

Error Assessment Of A Low Budget Precision Orbit Determination Program For A Low-Earth-Orbit Satellite Using GPS Observation Data
Jung Hyun Jo, Nammi Jo Choe, and John E. Cochran, Jr.; Auburn University

The development of a low budget precision orbit determination (LBPOD) program for use on-board, low-Earth-orbit (LEO) satellites and its application to a particular satellite are described. The program utilizes the Global Positioning System (GPS). Non-differenced LEO-GPS pseudo range measurements are used. A batch filter is used to provide statistical best state estimates. Results obtained for the LEO satellite, CHAMP (Challenging Mini-satellite Payload), are compared with those obtained with a current reference level precision orbit Determination (POD) program. The final orbit was estimated within anticipated errors with nominal initial state. Results obtained using four different models for the satellite dynamics are compared.

1600 AAS 03-229

Estimation Of Instantaneous Maneuvers Using A Fixed Interval Smoother
James Woodburn and John Carrico; Analytical Graphics, Inc.

An alternative to the typical means of maneuver reconstruction and calibration is presented which uses the orbit determination algorithm directly to provide an estimate of short duration orbital maneuvers. The proposed method uses a sequential filter and fixed interval smoother to estimate the satellite state forward and backward across the time of the maneuver. The resulting maneuver estimate, which is derived directly from the normal orbit determination process, is supplemented by the existence of an associated covariance. Examples of this process using both real and simulated tracking data will be presented in conjunction with a comparison to standard reconstruction and calibration methods using least squares.

1620 AAS 03-230

Precise Real-Time Satellite Orbit Determination Using The Unscented Kalman Filter

Deok-Jin Lee and Kyle T. Alfriend; Texas A&M University

In this article, an alternative generalization of the Extended Kalman filter, the Unscented Kalman Filter (UKF), is used for orbit determination. This paper points out the drawbacks in the EKF and shows how the UKF can overcome these drawbacks. The performance of UKF is equivalent to the KF for linear system and generalizes elegantly to nonlinear systems without the burdensome linearization. In addition, the method is not restricted to the assumption that the dynamic model and measurement errors are represented by Gaussian white noise. Numerical stabilized algorithms for the UKF are implemented to guarantee the positive definiteness of the covariance matrix.

1640 AAS 03-231

Determination of Satellite Formation Geometry and Phasing from Range Data

Trevor Williams, David Thompson, and Anees Syed; University of Cincinnati

The problem to be addressed in the paper is that of reconstructing the full geometry and phasing of a satellite formation from a limited set of data, specifically a time history of inter-satellite ranges. Such a capability would allow a set of small spacecraft that pass timing signals between each other (as required for radar interferometry missions) to obtain a complete description of their relative motion. This would be valuable for providing advance warning of satellite collisions, caused for instance by formation slippage due to differential drag effects, and for designing timely maneuvers to avoid such collisions.

Session 18: Orbital Dynamics

Chair: Felix Hoots
GRC International Inc.

1330 AAS 03-232

Properties of the Triangular Libration Points and some Mechanical Analogies
Roger A. Broucke; University of Texas (Plenary Lecturer)

We consider the two Triangular Lagrangian Libration points in the Restricted Problem of Three Bodies, with small mass ratio. We review some of the geometrical properties of the infinitesimal elliptic solutions around L4 and L5, dealing with the orientation in space and ratio between the axes of the infinitesimal ellipses. We compare this with the so-called "Double Pendulum", which has a stable equilibrium position, with both short and long-period librations around it. We show that, the small oscillations can be extended into large amplitude motions, with eventually many bifurcations, similarly to what is well known in the Restricted Three-Body Problem.

1350 AAS 03-233

On The Dynamic Behavior Of An Orbiter Around Europa
Martin Lara, Real Observatorio de la Armada, Spain; Juan F. San-Juan, Universidad de La Rioja, Spain

The dynamics of an orbiter close to a planetary satellite is known to be unstable from a wide range of inclinations encompassing polar orbits. Taking the Jupiter- Europa system as our model, we use numerically determined periodic orbits to investigate the stability of motion over three dimensional space for this problem. We found that the change in the stability is produced by a bifurcation in phase space: At a certain critical inclination, almost circular periodic orbits change their stability character to instability and new families of (stable) eccentric orbits appear.

1410 AAS 03-234

Analysis of Planetary Capture through Weak Stability Boundaries
Jesús Gil-Fernadez, Mariella Graziano, Paola Rogata, Edgar Milic, GMV S.A., Madrid.

Most interplanetary missions are characterised by severe requirements on the Delta-V budget to escape the Earth and to insert into nominal orbit. In the last years the natural tendency was to investigate about trajectory design techniques and "tricks" allowing reducing the Delta-V requirement for planetary capture. A good example of this tendency is the use of Weak Stability Boundary regions. The problem of planetary capture for inner, outer planets and natural moons is tackled considering three different reference missions: Bepi-Colombo, Venus Express and Europa-Orbiter. A simplified analytical approach explains the dynamic for the planetary capture occurrence.

1430 AAS 03-235

Numerical Investigation of Perturbation Effects on Orbital Classifications in the Restricted Three-Body Problem
Hideaki Yamato and David B. Spencer, Pennsylvania State University

Recently, a new class of trajectory design method based on dynamical systems theory has been vigorously researched. The qualitative information regarding dynamical flows in the phase space, provided mostly as a result of orbital classification, offers an effective framework for the trajectory design problem. In this study, the perturbation effect due to the other bodies on the orbital classification is examined in detail through numerical simulations. The design algorithm is then augmented so that trajectories can be designed with the presence of perturbing bodies. As another application, furthermore, the design method for the elliptic-restricted three-body system is also considered.

Break **1450–1520**

1520 AAS 03-236

Comparison of the DSST and the USM Semi-Analytical Orbit Propagators
P. J. Cefola, MIT/Lincoln Laboratory; V. S. Yurasov, Space Research Center “Kosmos”, Russia; Z. J. Folcik, E. B. Phelps, MIT/Lincoln Laboratory; R. J. Proulx; Charles Stark Draper Laboratory; , Center For Program Studies, Russia

This paper begins an effort to compare the accuracy and timing characteristics of the Draper Semianalytical Satellite Theory (DSST) developed in the USA and the Universal Semianalytical Method (USM) developed in Russia. The DSST and the USM share several characteristics: Both employ the Generalized Method of Averaging (GMA) Perturbation Theory; Both employ non-singular orbital elements; Both include comprehensive force modeling; Both consider numerical approximation of the slowly varying quantities. However, the development of these two theories has proceeded independently over more than 20 years up to the current time and there are many differences in the theories, as well.

1540 AAS 03-237

Long-Term Evolution of the KOMPSAT-1 Orbit
Byoung-Sun Lee, Jeong-Sook Lee, and Jae-Hoon Kim, Electronics and Telecommunications Research Institute (ETRI), Korea

More than two years of natural orbit evolution of the KORea Multi-Purpose SATellite-1 (KOMPSAT-1) from Sun synchronous orbit with altitude of 685 km is monitored and analyzed in this paper. The decay of the altitude is monitored with the Solar flux variation.

The shift of local time of ascending node is analyzed with the orbit inclination. The evolution of near frozen orbit is monitored and analyzed in a phase plot of the mean argument of perigee and mean eccentricity. Further orbital evolution of the KOMPSAT-1 is also predicted with the long-term mean orbit propagation.

1600 AAS 03-238

Models Of Motion In A Central Force Field With Quadratic Drag
M. Humi, Worcester Polytechnic Institute; T. Carter, Eastern Connecticut State Univ.

In this paper we first derive the general properties and integrals for the motion of a particle in a central force field with a general power-law drag. Under this setting exact and approximate solutions of the equations of motion are found in various cases. Emphasis is placed on inverse square gravitation and quadratic drag. In one model the altitude of a circular orbit is found to decay exponentially under quadratic drag. Approximation of the equations of motion for orbits in which either the tangential or radial speeds are relatively small leads to closed-form solutions for certain cases.

1620 AAS 03-239

Formulas For The Drag Constant And Time Of Flight In The Two-Body Problem With Quadratic Drag
M. Humi, Worcester Polytechnic Institute; T. Carter, Eastern Connecticut State Univ.

In a previous paper we presented certain closed-form solutions of the orbit equation for the two-body problem with drag that is quadratic in the magnitude of the velocity and inversely proportional to the distance from the center of attraction. An exact solution was presented for initially circular orbits and an approximate solution was presented for elliptical orbits of moderately low eccentricity. We present simple formulas for calculation of the drag constant and flight time in terms of the loss in altitude in the first case. In the second case approximate formulas for flight time are presented in terms of the orbit angle.

1640 AAS 03-240

The Clohessy-Wiltshire Equations can be Modified to Include Quadratic Drag
M. Humi, Worcester Polytechnic Institute; T. Carter, Eastern Connecticut State Univ.

The relative-motion equations of a spacecraft in the vicinity of a satelite in an orbit that is not highly eccentric but decays as a result of quadratic drag, are investigated. If the drag is quadratic in the magnitude of the velocity and varies inversely with the distance from the center of attraction, the equations simplify further. If the two objects in orbit have the samedrag constant and the initial orbit is circular, the equations reduce to an extension of the Clohessy-Wiltshire equations, modified to include quadratic drag.

Session 19: Mission Design-II

Chair: Jim McAdams
Applied Physics Laboratory

0800 AAS 03-241

Mission Planning for the Space Maneuver Vehicle
William E. Wiesel, Wright-Patterson AFB

Mission planning for the Air Force Space Maneuver Vehicle (SMV) requires wholesale solution of the Lambert problem about an oblate earth. We discuss numerical and algorithmic aspects of this solution, as well as the orbital element inverse problem: determining the orbital elements that yield a give position and velocity at a given time. A demonstration of the mission planning software is planned.

0820 AAS 03-242

Outer-Planet Mission Analysis Using Solar-Electric Ion Propulsion
Byoungsam Woo, Victoria L. Coverstone, John W. Hartmann, University of Illinois at Urbana-Champaign; Mike Cupples, Science Applications International Corporation Huntsville

Outer-planet mission analysis was performed with three solar-electric ion thruster models. Trajectories are generated using SEPTOP (Solar-Electric Propulsion Trajectory Optimization Program) and maximize the delivered mass to the designated outer planet. In this paper, trajectories to Saturn and Neptune are investigated. The trajectories have a single gravity assistant at Venus. In addition, the effect of available power generated by the solar arrays was studied. Finally, multiple locally optimal solutions to Neptune have been determined in different regions of the parameter search space.

0840 AAS 03-243

Heliocentric Earth Trailing Orbit Design for a Small Probe Concept
Emanuele Di Sotto, Lorenzo Tarabini, Mariella Graziano, GMV S.A., Madrid

This paper deals with the design of a Heliocentric Earth Trailing Orbit tailored on the particular requirements and mission constraints of SMART-2 probe (when the HETO was a studied option for SMART-2). This orbit has been optimised in order to minimise the drift from the Earth during the one year mission lifetime while keeping the Sun-probe-Earth angle as constant as possible. Such an orbit would provide a clean environment to both the spacecraft and the instrument without adversely stressing the communication system. The paper highlights the optimum performances provided by an out-of-ecliptic trajectory, which allows the probe to fulfil the communication constraints while maintaining the departure energy (C3) as small as possible.

0900 AAS 03-244

Preliminary Design Of Earth-Mars Cyclers Using Solar Sails
Robert Stevens and I. Michael Ross; Naval Postgraduate School, Monterey

Motivated by recent renewed interest in cycler trajectories, we design optimal Earth-Mars cyclers for spacecraft that use solar sails. The design is preliminary in the sense that the trajectories are assumed to be coplanar and the orbits of Earth and Mars are assumed to be circular. The optimality criterion is a weighted sum of the V_infinity at Mars and Earth. This trajectory optimization problem is formulated using the framework of optimal control and is numerically solved using the reusable dynamic optimization software, DIDO. Feasibility of the DIDO-derived trajectories is demonstrated using numerical propagation. Results show that solar sails can be used to significantly reduce V_infinity's at Mars and Earth. For example, a V_infinity(Mars) = 1 km/s is possible at every synodic period.

Break **0920–0950**

0950 AAS 03-245

Designing Phase 2 for the Double-Lunar Swingby of the Magnetospheric Multiscale Mission (MMS)
Ariel Edery, a.i. Solutions, Inc.

The Magnetospheric Multiscale (MMS) mission is a formation flying mission that consists of four distinct phases: phases 1 and 2 are low-inclination highly elliptical orbits (HEO) and phase 3 is a double-lunar swingby which transfers phase 2 to phase 4 where phase 4 is a highly-inclined orbit. Phase 2 is designed to reach the first lunar swingby of phase 3 in the most efficient fashion. It is shown that when the orientation of the line of apsides of phase 2 is properly chosen, no extra Delta-V is required beyond what is typically needed to raise apogee to lunar distance.

1010 AAS 03-246

Study on Recovery of Escape Missions
Stefania Cornara, Miguel Belló-Mora, DEIMOS SPACE S.L., Spain; Martin Hechler, ESA-ESOC, Germany

The high operational risk involved in escape missions requires a rapid and effective reaction capacity whenever a critical failure occurs. To address this need, DEIMOS SPACE has accomplished a study to enable the systematic analysis of possible recovery strategies in case of failure or under-performance during the launch and Earth escape of "on-the-way" ESA missions (Rosetta and Mars Express). The mission analysis tool developed encompasses such recovery strategies as manoeuvres for direct transfers, sequences of planetary gravity assists, lunar gravity assists (potentially combined with weak stability boundaries) and mission re-design options. This paper presents a comprehensive overview of the algorithms developed to handle the escape mission recovery and the results obtained.

1030 AAS 03-247

The CloudSat Mission: A Virtual Platform

Ronald J. Boain, Jet Propulsion Laboratory

CloudSat's science team decided from the beginning to capitalize on the synergy between CALIPSO's lidar measurements, Aqua's MODIS measurements, and observations made by CloudSat's Cloud Profiling Radar in making the most comprehensive studies possible of clouds and their impact on climatologically forecasting. The science team requested that CloudSat's mission design accommodate requirements on simultaneity and coincidence of measurements to form, in effect, a "virtual platform" of three satellites. This paper describes the mission design for CloudSat that enables and creates this virtual platform. It describes how CloudSat establishes a formation with a separation from its closest partner of only 15-seconds and is still always within 90 seconds of the other partner. It further describes how CloudSat will be controlled to ensure an acceptable level of operational risks in terms of launch, orbit acquisition, orbit maintenance, and collision avoidance.

Session 20: Navigation and Orbit Determination-Operations-II

Chair: Thomas Alan Lovell
Air Force Research Laboratory

0800 AAS 03-248

Characterization of Space Surveillance Sensors Using Normal Places

John H. Seago, Mark A. Davis, Honeywell Technology Solutions, Inc.; Anne E. Reed, Naval Research Laboratory

Normal place formation is a century-old technique that is still widely practiced in orbit determination. A "normal place" is a measurement combined from several closely associated observations of an orbiting body. Although normal place reduction of artificial satellite tracking was advocated by Herrick as late as 1959, normal points are not explicitly used by the centers processing US Space Surveillance Network observations. In this paper we suggest pre-processed normal places as an alternative measurement for general orbit determination and sensor performance characterization, and describe the relevant techniques used in their experimental normal place transformations of full rate satellite tracking data.

0820 AAS 03-249

Navigation For The Mars Premier Netlander Delivery

Stéphanie Delavault, Laurent Francillout, Denis Carbonne, Hubert Fraysse, CNES, France; P. Daniel Burkhart, Diane Craig, Joseph Guinn, NASA/JPL

One challenging phase of the MARS PREMIER mission is the release of four Netlanders to the Martian soil. From a navigation point of view, this deployment requires a high accuracy level for the Netlander trajectory entry, which is difficult to obtain with only radio data. This paper presents covariance and propulsive maneuver analyses performed to determine the impact on navigation performance of parameters such as the addition of DDOR measurements, tracking data schedule, and maneuver execution errors. Conclusions are drawn on navigation needs and an assessment is made of the robustness of navigation performance for the Netlander deployment phase.

0840 AAS 03-250

Approach Navigation for the 2009 Large Lander

P. Daniel Burkhart, Jet Propulsion Laboratory

The current Mars exploration plan envisions the launch of a large lander in the 2009 launch opportunity with a soft landing on Mars in the fall of 2010. The goal is to achieve

a landed surface position within 10 km of the target landing site. Current entry descent and landing (EDL) analysis shows that the largest contributor to the landed position error is uncertainty of the initial conditions, which are supplied by the ground-based navigation process. The focus of this paper is the performance of the approach navigation process using combinations of Deep Space Network (DSN) Doppler, ranging and double-differenced one-way range (Delta-DOR) measurements along with optical navigation data collected by the spacecraft. Results for several combinations of data types will be included.

0900 AAS 03-251

Orbit Of Mars Explorer NOZOMI And Its Determination By Delta-VLBI Technique

Makoto Yoshikawa, Jun'ichiro Kawaguchi, Hiroshi Yamakawa, Takaji Kato, Tsutomu Ichikawa; Institute of Space and Astronautical Science, Japan; Takafumi Ohnishi, Shiro Ishibashi, Fujitsu Limited, Japan

The Japanese Mars explorer NOZOMI has several difficult problems in its orbit determination. The most difficult one is that the range and/or range-rate data cannot be obtained for some periods because we cannot turn the high gain antenna toward the earth due to the attitude constraint. Therefore we considered the orbit determination by the delta-VLBI method. At first we carried out some simulations and showed that the delta-VLBI data is very effective. Next we tried to carry out actual observation by delta-VLBI in collaboration with some groups in Japan. Our aim is to put delta-VLBI method to practical use.

Break **0920–0950**

0950 AAS 03-252

Radiometric Orbit Determination Activities In Support Of Navigating Deep Space 1 To Comet Borrelly

Brian M. Kennedy, Shyam K. Bhaskaran, Joseph E. Riedel, and Mike Wang, Jet Propulsion Laboratory

In summer of 2001, en route to its encounter with Comet Borrelly, the DS1 spacecraft had critical difficulties maintaining on board knowledge of inertial attitude. Correcting these losses of attitude had a continual impact on the near constant low-thrust mission profile. Successfully modeling this attitude impact to maintain the OD allowed for timely redevelopment of mission burn profiles, and insured success of the DS1 mission as it began the important approach phase of it's encounter with Comet Borrelly.

1010 AAS 03-253

GRACE Precise Orbit Determination

Z. Kang, B. Tapley, S. Bettadpur, P. Nagel, R. Pastor, University of Texas Center for Space Research

One of the key science instruments aboard GRACE is the K-Band Ranging (KBR) system, which measures the dual one-way range change between both GRACE satellites with a precision of about 1 micrometer per second. These measurements together with GPS tracking data are used in GRACE precise orbit determination (POD) and for gravity field recovery. The GRACE orbits can be determined with an accuracy of approximately 5 cm in each direction by using GPS tracking data. KBR is a Satellite-to-Satellite Tracking (SST) in the low-low configuration. It is shown that the KBR data can be used to improve the along-track orbit accuracy and accuracy of the relative distance between two GRACE satellites. The preliminary results indicate that the orbit accuracy is about 10 cm RMS in 3D position and relative accuracy is at the millimeter level.

1030 AAS 03-255

The Trajectory Of A Photon: General Relativity Light Time Delay

James K. Miller, Jet Propulsion Laboratory

The transit time of a photon or electromagnetic wave between two points in space is a measurement that is used to determine the orbits of the planets and spacecraft for the purposes of navigation and science. Both the navigation of a spacecraft and science experiments, particularly associated with General Relativity, require precise measurements of the transit time. Since the Deep Space tracking stations can measure times to within 0.1 ns or about 3 cm, it is necessary to model the transit time to this accuracy. In this paper, a formula is developed for the total one-way transit time of a photon in the coordinate time of General Relativity. A bending term is identified that contributes about 10 ns to the transit time of a photon that grazes the Sun and is not generally included in other formula in the literature. The results are verified by performing numerical integration of the equations of motion for a photon. A numerical photon ephemeris is computed and compared with the analytic formula.

1050 AAS 03-254

WITHDRAWN

AUTHOR INDEX

Notes

RECORD OF MEETING EXPENSES

13th AAS/AIAA Space Flight Mechanics Meeting
Ponce Hilton Hotel
Ponce, Puerto Rico
February 9–13, 2003

Name: ____________________ Organization: ____________________

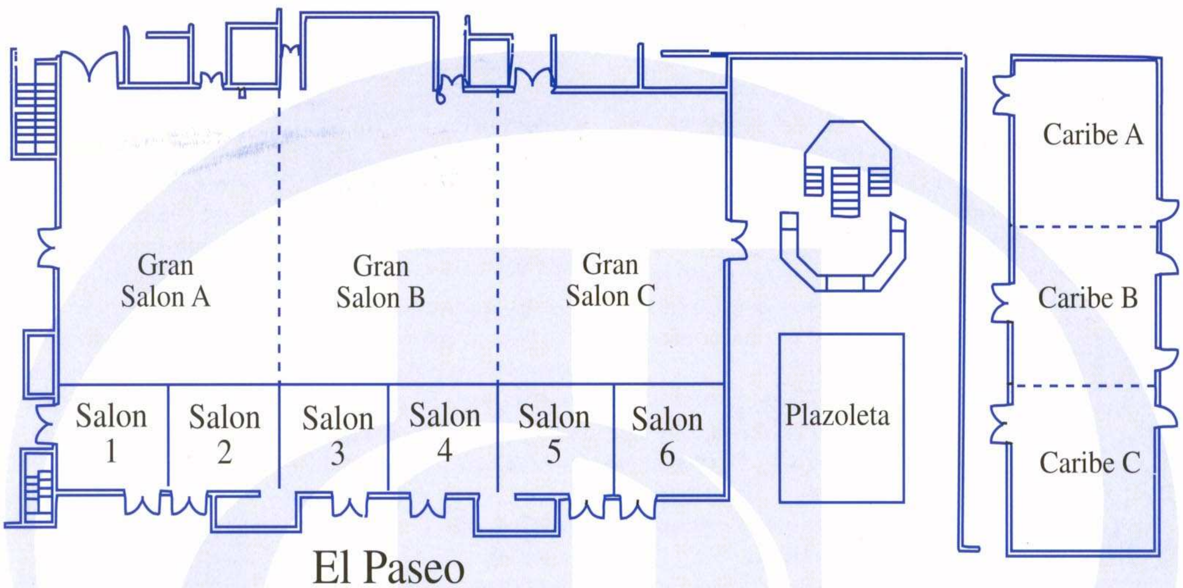
Registration Fee: AAS or AIAA Member $225	____________
Non-Member @ $310	____________
Student @ $50	____________
Conference Proceedings @ $190	____________
Technical Paper Sales @ $2.00 per paper	____________
Barbecue @ $25 adult, $10 child under 12	____________
Arecibo Tour:	
Bus @$10	____________
Admission @$4 adult, $2 child	____________
Box Lunch @$15	____________
TOTAL:	____________

Technical Paper Purchases

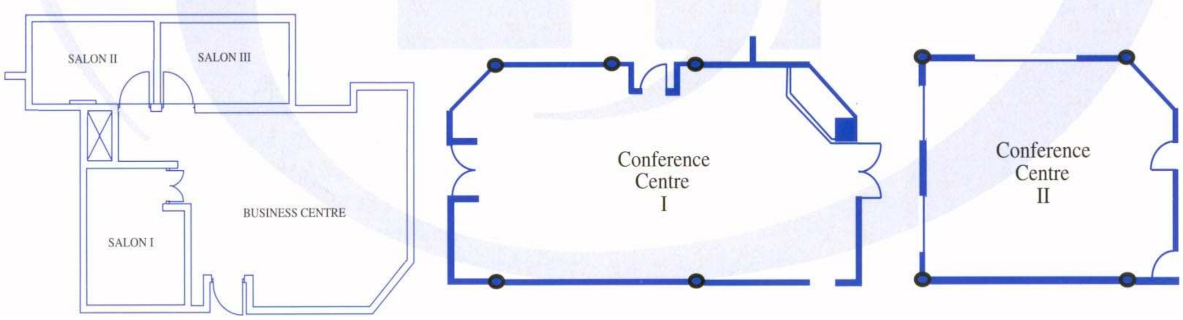
# of Papers	Cost	Date

Meeting facilities

Level 1 (Ground Floor)



Level 2 (Lobby Area)



PROGRAM AT A GLANCE

	Sunday **9 February**	**Monday** **10 February**	**Tuesday** **11 February**	**Wednesday** **12 February**	**Thursday** **13 February**
Registration	1600–1900	0700–1600	0700–1600	0700–1600	0700–1100
Speakers' Breakfast		0700–0800 Salon 5+6	0700–0800 Salon 5+6	0700–0800 Salon 5+6	0700–0800 Salon 5+6
Morning Sessions 0800–1110		Attitude Control Conference Center I	Attitude Determination and Control Missions Conference Center I	Attitude Determination and Dynamics Conference Center I	Mission Design-II Caribe B
		Formation Flight-I Caribe B	Navigation and Control Caribe B	Navigation and Orbit Determination-Operations-I Caribe B	Navigation and Orbit Determination-Operations-II Caribe C
		Optimization Caribe C	Orbit Determination Caribe C	Mission Design-I Caribe C	
Committee Lunches		AIAA Astrodynamics TC 1130–1330 Salon 5+6	AAS Space Flight Mechanics TC 1130–1330 Salon 5+6	AAS Space Flight Mechanics TC II 1130–1330 Salon 5+6	
Afternoon Sessions 1330–1640		Attitude Determination and Control–Hardware Conference Center I	Space-Based Interferometry Conference Center I	Tethers Conference Center I	
		Formation Flight-II Caribe B	Constellations Caribe B	Orbit Determination-II Caribe B	
		Optimization and Orbital Transfers Caribe C	Orbital Debris Caribe C	Orbital Dynamics Caribe C	
Special Events	Early Bird Reception Gran Salon A+1+2 1900–2200	Brouwer Award Lecture Gran Salon C 1700–1800 General Reception Gran Salon B+3+4 1830–2100	Guest Speaker from Aricebo Observatory Gran Salon C 1700–1800 Poolside Barbecue 1830–2300	Evening Free	Arecibo Field Trip Hotel Lobby 1200–1800