Conference Program

14th Space Flight Mechanics Meeting

8 – 12 February 2004
Wailea Marriott
Maui, Hawai'i

American Astronautical Society

AIAA

American Institute of Aeronautics and Astronautics

AAS General Chair
Kim Luu
Air Force Research Laboratory

AAS Technical Chair
Shannon Coffey
Naval Research Laboratory

AIAA General Chair
Robert Glover
AT&T Government Solutions, Inc.

AIAA Technical Chair
Andre Mazzoleni
North Carolina State University

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General Information

Registration

The following registration fees are in effect for this conference:

- AAS or AIAA Members **$310.00**
- Nonmembers (includes one year membership in the AAS) **$395.00**
- Full-time Students **$200.00**
- Retired Professionals **$200.00**

Conference Proceedings

The proceedings are available for purchase at a reduced prepublication cost. A four-volume hardcover set and CD-ROM will be issued. Orders for the proceedings are accepted at the registration desk. The costs are

- Conference Rate **$280.00**
- Post-published List Price **$600.00 (approximate)**
- List Price with Author Discount **$300.00 (approximate)**

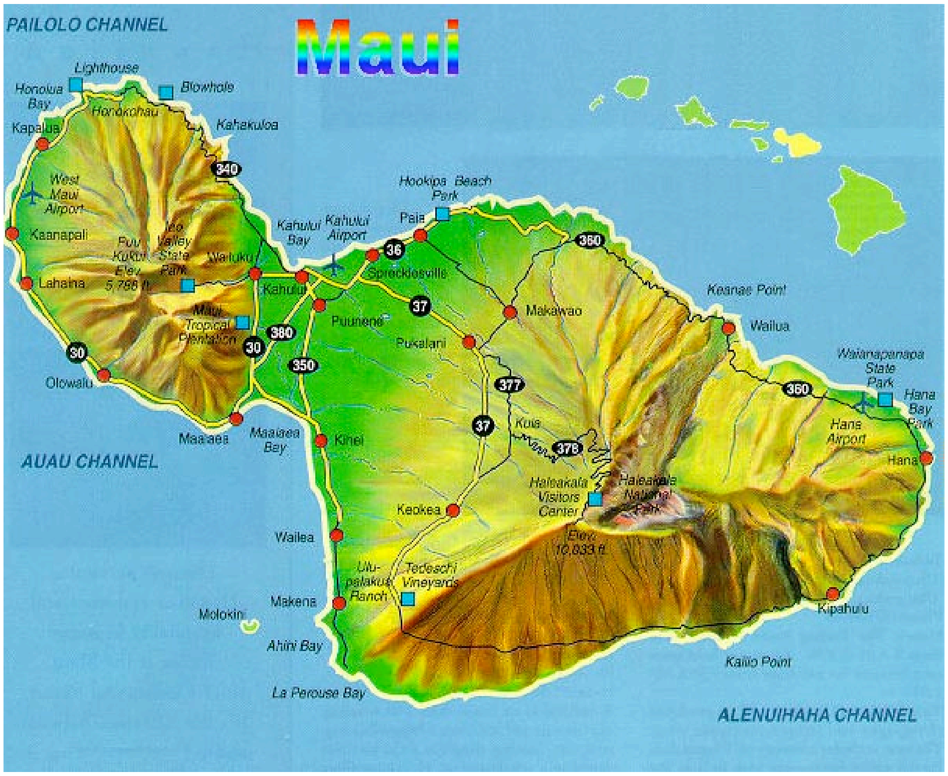
Conference Location

Maui is one of the most remarkable places on Earth. The Valley Isle is blessed with natural beauty, pleasant climate, varied terrain and coastline, abundant flora and fauna, rich cultural history, and gentle society. Geographically speaking, the island is approximately 48 by 26 miles totaling 728 square miles, second largest among the Hawaiian Islands. The landmass is roughly divided between the older West Maui mountains, stately Haleakala to the south, and connecting them, a narrow isthmus forming Central Maui. The local population of 130,000 makes up a diverse society with many Pacific Rim, European, and Caribbean cultures contributing to the mainstream. Hawaiian and Polynesian influences are evident in everyday life, from language to cuisine. The tourism industry brings big-city amenities, including fine dining, world-class resorts and spas, numerous retailers and galleries, and an abundance of activity providers. Harmonious combinations of luxurious resort areas and pastoral countryside, sunny beaches and lush rainforest, and balmy coastlines and the stark crater of Haleakala delineate the environment of Maui.

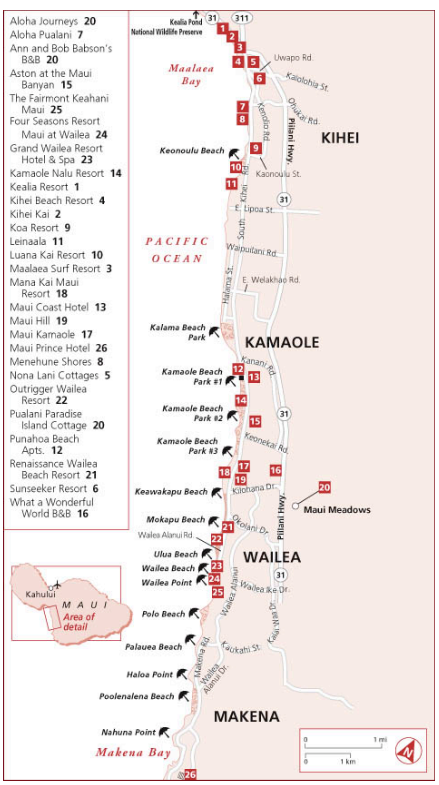
Area Attractions and Activities

Activities abound to fill leisure hours. Beaches are rarely crowded, and conditions for water sports are ideal. Other choices include golf, tennis, biking, hiking, caving, horseback riding, and visiting historical and cultural attractions. The undisputed highlight of the winter season is the annual migration of North Pacific humpback whales to the Hawaiian Islands to mate and give birth. These wonderful creatures are frequently spotted in the channel between Maui and Lanai and Kaho'olawe. Some recommended activities include visits to the Maui Ocean Center, Iao Valley, Haleakala National Park (both summit and Kipahulu areas), the black sand beach at Waianapanapa, and the spectacular red sand beach near Hana, taking a whale-watching cruise and a helicopter tour of the island, snorkeling or diving in Makena, at Molokini, and off Ulua Beach, driving to Hana through the waterfall-studded rainforest, watching the surfers at Hookipa, and kayaking, canoeing, or hiking the Keoneoio coast.

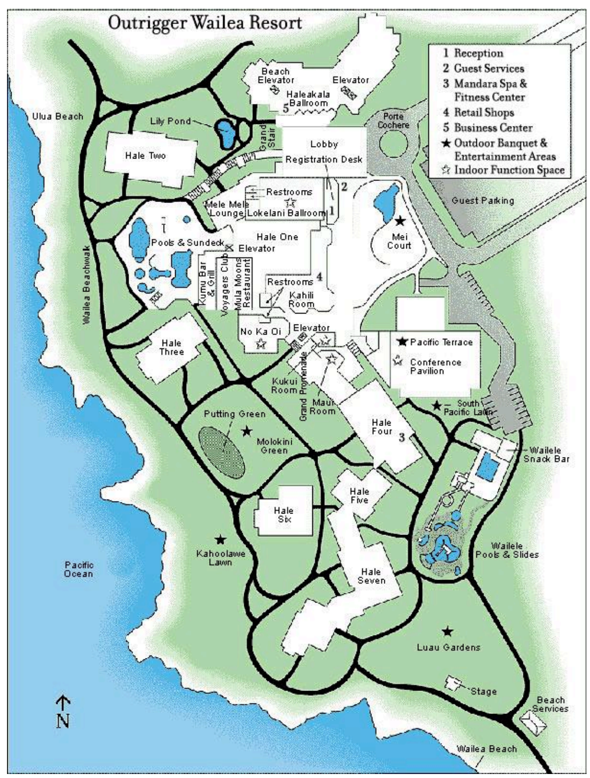
Maps



Maui
PAILOLO CHANNEL
Lighthouse
Honolua Bay
Blowhole
Honokohau
Kahakuloa
Kapalua
340
West Maui Airport
Kaanapali
Puu Kukui Elev. 5,788 ft.
Iao Valley State Park
Wailuku
Kahului Bay
Kahului Airport
Hookipa Beach Park
Paia
36
360
Sprecklesville
Kahului
Lahaina
Maui Tropical Plantation
380
30
Puunene
37
Makawao
Keanae Point
Wailua
Pukalani
350
Olowalu
377
Waianapanapa State Park
Hana Bay Park
Hana Airport
Maalaea
Maalaea Bay
Kihei
Kula
378
AUAU CHANNEL
Hana
Haleakala Visitors Center
Haleakala National Park
Keokea
Elev. 10,023 ft
Wailea
Ulupalakua Ranch
Tedeschi Vineyards
Makena
Molokini
Kipahulu
Ahihi Bay
Kaupo Point
La Perouse Bay
ALENUIHAHA CHANNEL

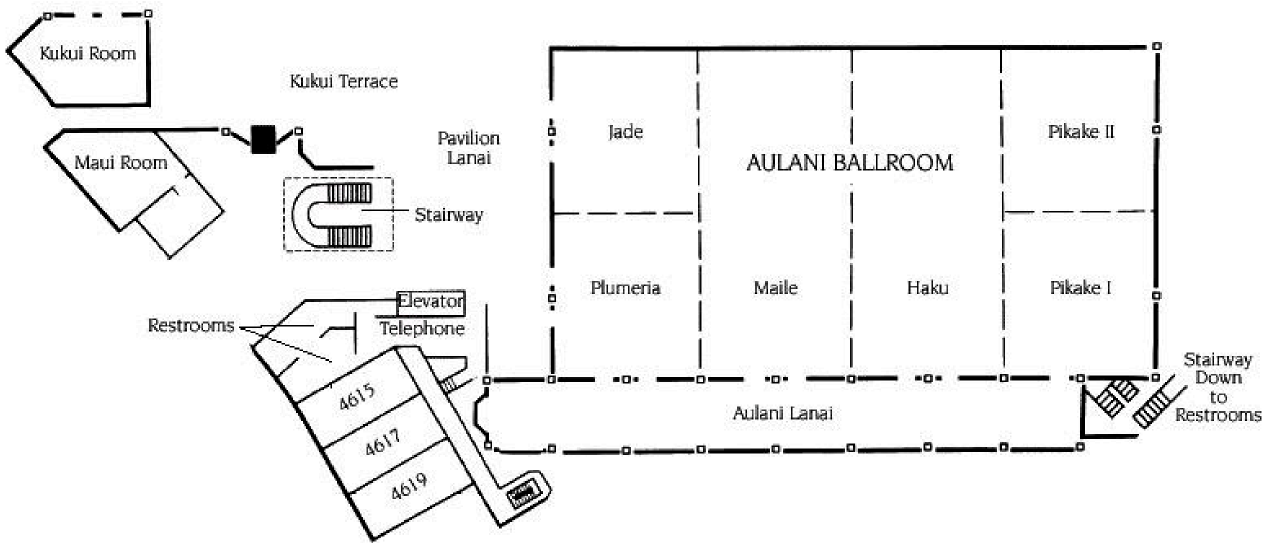


Aloha Journeys 20
Aloha Pualani 7
Ann and Bob Babson's B&B 20
Aston at the Maui Banyan 15
The Fairmont Keahani Maui 25
Four Seasons Resort Maui at Wailea 24
Grand Wailea Resort Hotel & Spa 23
Kamaole Nalu Resort 14
Kealia Resort 1
Kihei Beach Resort 4
Kihei Kai 2
Koa Resort 9
Leinaala 11
Luana Kai Resort 10
Maalaea Surf Resort 3
Mana Kai Maui Resort 18
Maui Coast Hotel 13
Maui Hill 19
Maui Kamaole 17
Maui Prince Hotel 26
Menehune Shores 8
Nona Lani Cottages 5
Outrigger Wailea Resort 22
Pualani Paradise Island Cottage 20
Punahoa Beach Apts. 12
Renaissance Wailea Beach Resort 21
Sunseeker Resort 6
What a Wonderful World B&B 16
Kealia Pond National Wildlife Preserve
Maalaea Bay
Uwapo Rd.
Kaiolohia St.
Ohukai Rd.
Kenolio Rd.
Piilani Hwy.
KIHEI
Keonoulu Beach
Kaonoulu St.
South Kihei Rd.
E. Lipoa St.
PACIFIC OCEAN
Waipuilani Rd.
E. Welakhao Rd.
Halama St.
Kalama Beach Park
KAMAOLE
Kanani Rd.
Kamaole Beach Park #1
Kamaole Beach Park #2
Kamaole Beach Park #3
Keonekai Rd.
Keawakapu Beach
Kilohana Dr.
Maui Meadows
Mokapu Beach
Okolani Dr.
Wailea Alanui Rd.
Ulua Beach
Wailea Beach
Wailea Point
WAILEA
Wailea Ike Dr.
Kahului
MAUI
Area of detail
Polo Beach
Palauea Beach
Kaukahi St.
Makena Rd.
Wailea Alanui Dr.
Kai Waa Dr.
Haloa Point
Poolenalena Beach
MAKENA
Nahuna Point
Makena Bay
1 mi
1 km

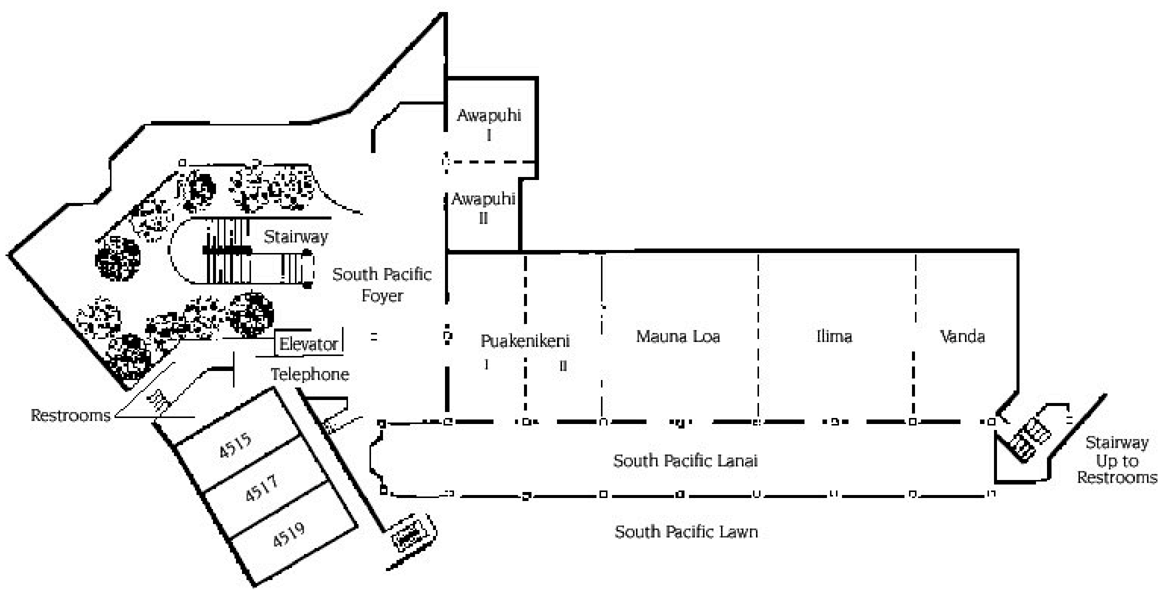


Outrigger Wailea Resort
1 Reception
2 Guest Services
3 Mandara Spa & Fitness Center
4 Retail Shops
5 Business Center
★ Outdoor Banquet & Entertainment Areas
☆ Indoor Function Space
Beach Elevator
Elevator
Haleakala Ballroom
Ulua Beach
Lily Pond
Grand Stair
Porte Cochere
Lobby
Registration Desk
Hale Two
Restrooms
Mele Mele Lounge
Lokelani Ballroom
Guest Parking
Hale One
Pools & Sundeck
Elevator
Mei Court
Kumu Bar & Grill
Voyagers Club
Mula Moons Restaurant
Restrooms
Kahili Room
Wailea Beachwalk
No Ka Oi
Elevator
Hale Three
Pacific Terrace
Conference Pavilion
Kukui Room
Grand Promenade
Maui Room
South Pacific Lawn
Putting Green
Molokini Green
Hale Four
Wailele Snack Bar
Hale Five
Hale Six
Kahoolawe Lawn
Wailele Pools & Slides
Pacific Ocean
Hale Seven
Luau Gardens
Stage
N
Beach Services
Wailea Beach

Aulani Ballroom – Lobby Level South
Conference Pavilion – 13,800 sf



South Pacific Ballroom – Conference Level South
Conference Pavilion – 4,600 sf



Sunset Cocktail Reception

All registered attendees and their guests are invited to the Sunset Cocktail Reception to be held oceanfront at the Kaho'olawe Lawn on the grounds of the Wailea Marriott on Sunday evening from 5:00 PM to 7:00 PM. Join us for drinks and heavy pupus (hors d'oeuvres) and catch up with friends and colleagues.

Aloha Tuesday

Attendees are encouraged to wear Aloha Attire at all conference functions on Tuesday. Using the attached ballot, you can cast your vote for the colleague who best embodies the Aloha spirit. Please write only one name and return the ballot to the registration desk before 2:00 PM on Tuesday afternoon. Prizes for winners:

- First place (most votes): 2 tickets on a Whale-Watching Cruise
- Second place: 2 tickets to Maui Ocean Center
- Third place: Matted photo of beautiful Maui scene

Winners must be registered for the conference.

Wailea's Finest Luau

Included with registration is a ticket to Wailea's Finest Luau at the Wailea Marriott on Tuesday evening beginning at 5:00 PM in the oceanfront Luau Gardens. An authentic Hawaiian Hula Show is complemented with spectacular Luau Buffet and open bar with tropical cocktails. The Luau Buffet includes

- Variety of Island Salads
- Imu Baked Kalua Pig
- Sauteed Mahi Mahi
- Grilled Teriyaki Steak
- Lau Lau
- Chicken Long Rice
- Hawaiian Sweet Potatoes
- Freshly Baked Taro Rolls
- Hawaiian Fried Rice
- Stir-Fry Vegetables
- Desserts: Macadamia Nut Cake, Banana Cream Pie, Haupia, Tropical Fruit Cobbler, Fresh Maui Pineapple, Papaya Slices, and More

Additional tickets may be purchased at the registration desk for the discounted group rate of $55.

Outrigger Canoe Paddling with the Wailea Canoe Club

For the adventurous, the state champion Wailea Canoe Club offers all attendees and their guests an opportunity to experience the quintessential Hawaiian sport, outrigger canoe racing. Participants will meet at Cove Park in Kihei at 7:00 AM on Thursday morning. Instruction, equipment, and bottled water will be provided along with breakfast after an invigorating 1-hour session. Six-man canoe paddling emphasizes technique, team work, and physical endurance. After a short on-land introduction, we will launch the canoes and practice proper technique in preparation for short sprint races at the conclusion of the session. A variety of marine creatures may be spotted while on the water, including green sea turtles, manta rays, spinner dolphins, and humpback whales. Participants should dress to get wet. Sign up for this activity at registration. Fees are $10 for individuals and $15 for families. All participants must be able to swim and must sign a liability release waiver.

Driving instructions from Wailea Marriott to Cove Park:
From the hotel, turn left to go north on Wailea Alanui Dr. for 0.2 miles. Turn left at the stop sign to head towards the ocean on Okolani Dr. After 0.3 miles, Okolani curves right to become S. Kihei Rd. Continue on S. Kihei Rd for approximately 2.3 miles to Cove Park. Look for the white canoes on the ocean side. Parking is readily available at Kalama Beach Park, just past Cove Park on the left.

Tour of Air Force Maui Optical and Supercomputing (AMOS) Site

The AMOS site encompasses the Maui High Performance Computing Center (MHPCC), the Maui Space Surveillance System (MSSS), and the Remote Maui Experiment site. These facilities are managed by the Air Force Research Laboratory (AFRL) Directed Energy Directorate with the unifying mission of satisfying DOD research and operational objectives, focusing on advanced electro-optical technologies, developing state-of-the-art systems, advancing high performance computing capabilities, and delivering quality information to a broad spectrum of customers.

The MHPCC offers large-scale parallel computing platforms with terabytes of disk and on-line tape storage, and a high-speed communications infrastructure that connects directly to the Defense Research and Engineering Network. Through this facility, researchers have access to state of the art hardware, software, tools, and expertise to support activities such as image and signal processing, modeling and simulation, and training and education. The MSSS is located near the summit of Haleakala providing outstanding observing conditions year round. Several optical systems are situated at MSSS, including the 0.36m (14.5") Raven telescope, 0.6m laser beam director, 0.8m laser beam director/tracker, two 1.2m telescopes on a common mount, 1.6m telescope, and 3.6m Advanced Electro-Optical System telescope. The MSSS is a contributing sensor for the Air Force Space Command Space Surveillance Network.

Conference attendees with advance reservations for this sold-out tour will meet on the Pavilion Lanai at 10:45 AM on Thursday morning. Please bring a photo ID to check in. The motorcoach will depart the Wailea Marriott promptly at 11:00 AM for the short drive to the Maui Research and Technology Park in Kihei. There we will receive an overview of the AMOS site and demonstration of the visualization lab while enjoying a catered lunch. Next we will depart for the 1.5-hour drive to the MSSS, situated near the summit of Haleakala ("House of the Sun"). This scenic drive will take us from sea level to 10,000 ft elevation through the serene Upcountry districts of Maui. After visiting MSSS and with time/weather permitting, we will make a brief stop at the Summit House of Haleakala National Park to enjoy the spectacular views. We will return to the hotel ending the tour at approximately 1800.

Cameras, cell phones, and other electronic devices will not be allowed in the government facilities so if you choose to bring these items, you must leave them in the motorcoach while touring the facilities. Please note that the weather at the summit is unpredictable and may be dramatically cooler. Jacket and sunglasses are suggested, and closed-toe shoes are required.

Technical Program

Technical Sessions

- This conference presents 201 papers on space flight mechanics and related topics in 24 full sessions, of which five are special sessions described more fully below. Four sessions run in parallel each morning and afternoon of the conference for three days.
- Morning sessions start at 8:30 AM and usually end by 12:00 PM. Lunch break is scheduled for 1.5 hours. Afternoon sessions commence at 1:30 PM and usually conclude by 5:00 PM.
- The sessions break for 20 minutes each morning and afternoon. Refreshments are served on Pavilion Lanai.
- The meeting rooms are adjacent to each other on the lobby level of the Conference Pavilion.

Special Sessions

- The **Solar Sails I** session will be held Monday morning in the Pikake Room.
- The **ACS Sensor Alignment and Calibration** session will be held Monday morning in the Haku Room.
- The **Space Surveillance Processing** session will be held Monday morning in the Maile Room.
- The **Optical Satellite Tracking Systems** session will be held Tuesday morning in the Maile Room.
- The **Solar Sails II** session will be held Wednesday afternoon in the Pikake Room.

Plenary Sessions

- Dr. Joseph Janni, the Director Emeritus of the Air Force Office of Scientific Research, will present the keynote address on Monday morning at 8:30 AM in the Maile Room. Dr. Janni is currently affiliated with the Air Force Maui Optical and Supercomputing Site.
- Dr. David Dunham, the 2003 Dirk Brouwer Award recipient, will give a lecture on Monday evening at 5:00 PM in the Maile Room. The Brouwer Award was established to honor significant technical contributions to space flight mechanics and astrodynamics and to recognize Dirk Brouwer's outstanding role in celestial mechanics and his widespread influence on workers in space flight and astrodynamics. We will also present the Breakwell Student Travel Award and the Best Paper Award.

Presentations

- Each presentation is allocated 20 minutes total time, including questions and any preliminary setup. Session chairs will maintain this pace to assure that presentations proceed according to the posted schedule.
- Each room will be equipped with an overhead projector for transparent viewgraphs and also a computer and projector. Authors should contact their session chairs to get their presentations loaded if using the computer projection system.
- The NO PAPER NO PODIUM rule will be enforced. The session chairs will verify the delivery of a reproducible plus 50 copies for every presentation in their sessions by the end of the applicable Speakers Breakfast (see below). Lack of such timely delivery will constitute withdrawal of the paper.

Speakers Breakfast

Authors who are making presentations and session chairs of the day will meet in the Mauna Loa/Ilima Room for a short briefing at 7:30 AM on the morning of their session. A continental breakfast will be served.

Paper Sales

Authors are required to bring 50 copies of their paper to the conference. The preprints will be on sale for $1.00 per paper in the Jade room adjacent to the meeting rooms. Bound copies of the conference proceedings may be ordered at the registration desk.

Committee Meetings

Committee meetings will be held according to the following schedule in the Mauna Loa Room:

AIAA Astrodynamics TC	Monday	12:00 – 1:30 PM
AAS Space Flight Mechanics TC	Tuesday	12:00 – 1:30 PM

Schedule of Events

Date/Time	Event	Location
Saturday, 7 February		
1300–1600	Registration	Kukui Terrace
Sunday, 8 February		
1300–1600	Registration	Pavilion Lanai
1600–1800	Sunset Cocktail Reception	Kaho'olawe Lawn
Monday, 9 February		
0700–1700	Registration	Pavilion Lanai
0730–0830	Speakers Breakfast	Mauna Loa/Ilima
0800–1700	Paper Sales	Jade
0830–0900	Keynote Address	Maile
0900–1120	Solar Sails I	Pikake
0900–1140	Orbital Mechanics I	Plumeria
0900–1200	ACS Sensor Alignment & Calibration	Haku
0900–1200	Space Surveillance Processing	Maile
1020–1040	Morning Break	Pavilion Lanai
1200–1330	AIAA Astrodynamics TC Mtg	Mauna Loa
1330–1650	Interplanetary Missions I	Haku
1330–1630	Attitude Dynamics & Control I	Pikake
1330–1650	Optimization & Control I	Plumeria
1330–1630	Formation Flying I	Maile
1510–1530	Afternoon Break	Pavilion Lanai
1700–1830	Awards Presentation & Brouwer Lecture	Maile
Tuesday, 10 February		
0730–0830	Speakers Breakfast	Mauna Loa/Ilima
0800–1700	Registration & Paper Sales	Jade
0830–1150	Tether Satellite Systems	Haku
0830–1210	Collision Avoidance, Debris & Atm Drag	Plumeria
0830–1130	Attitude Dynamics & Control II	Pikake
0830–1130	Optical Satellite Tracking Systems	Maile
1010–1030	Morning Break	Pavilion Lanai
1200–1330	AAS Space Flight Mechanics TC Mtg	Mauna Loa
1330–1630	Optimization & Control II	Maile
1330–1710	Orbital Mechanics II	Plumeria
1330–1650	Orbit Determination I	Haku
1330–1650	Interplanetary Missions II	Pikake
1510–1530	Afternoon Break	Pavilion Lanai
1700–2100	Luau	Luau Gardens

Wednesday, 11 February

0730–0830	Speakers Breakfast	Mauna Loa/Ilima
0800–1700	Registration & Paper Sales	Jade
0830–1130	Orbit Determination II	Haku
0830–1150	Orbital Mechanics III	Plumeria
0830–1150	Formation Flying II	Maile
0830–1110	Optimization & Control III	Pikake
1010–1030	Morning Break	Pavilion Lanai
1330–1710	Interplanetary Missions III	Haku
1330–1650	Solar Sails II	Pikake
1330–1650	Orbital Mechanics IV	Plumeria
1330–1650	Formation Flying III	Maile
1510–1530	Afternoon Break	Pavilion Lanai

Thursday, 12 February

0700–0900	Outrigger Canoe Racing	Cove Park, Kihei
1100–1700	AMOS Tour	Pavilion Lanai

Monday, February 9, 9:00 AM Pikake

Session 1: Special Session: Solar Sails I

Chair: Mike Lisano
Jet Propulsion Laboratory

9:00 AM **AAS 04-100** **Sailcraft Coordinate Systems and Format for Reporting Propulsive Performance**
Billy Derbes and David Lichodziejewski, L'Garde, Inc.; Jordan Ellis, JPL; and Daniel Scheeres, The University of Michigan

In designing solar sail structures, structural engineers must calculate structural loading and resulting deflections. Byproducts of this analysis are the integrated external solar pressure forces and moments on the mainsail and vanes, as well as mass properties. These are to be used to insert attitude or vane commands and propagate the resulting solar sail trajectories and/or attitudes. This paper presents a format for reporting forces, moments, and mass properties, along with reference coordinate systems.

9:20 AM **AAS 04-101** **Cosmos 1: The World's First Solar Sail Spacecraft**
V.M. Gotlib, V.M. Linkin, and A.N. Lipatov, Russian Academy of Sciences; K.M. Pitchkhadze and V.A. Kudryashov, Babakin Research Center, Russia; L. Friedman, The Planetary Society; J. Cantrell, Strategic Space Development; G. Delory, Space Sciences Laboratory; and Austin Chertkow, The Planetary Society

The privately funded attempt to develop and fly the first solar sail spacecraft, Cosmos 1, will be described. The spacecraft is slated for launch on the Russian converted submarine launched ballistic missile in the spring of 2004. The mission will be launched into a near polar, circular orbit with an initial altitude of approximately 800 km. The spacecraft and mission design will be discussed, with emphasis on achieving the prime mission goal: controlled solar sail flight to increase the orbital energy. Program objectives of The Planetary Society, and the sponsoring partner, Cosmos Studios, along with those of the Russian space organizations participating in the project will also be described.

9:40 AM **AAS 04-102** **The Geostorm Warning Mission: Enhanced Opportunities Based on New Technology**
John L. West, JPL

The Geostorm Warning Mission is a potential National Oceanic and Atmospheric Administration (NOAA) mission with the objective of obtaining solar storm warning data from a satellite positioned at a station slightly displaced from the Earth-Sun line at or nearer to the Sun than 0.98 AU, inside the Earth's L1 point at 0.993 AU. The Jet Propulsion Laboratory's (JPL) 1999 Space Technology-5 (ST-5) proposal could enable a factor of 2 increase in warning time compared to a conventional satellite at the L1 point. This paper discusses how advances in sail technology and new sailcraft design approaches can improve warning time.

10:00 AM **AAS 04-103** **NASA's Integrated Development of Solar Sail Propulsion**
Gregory Garbe, Edward E. Montgomery IV, and A.F. Heaton, NASA MSFC; and John T. Van Sant and Bruce A. Campbell, NASA GSFC

Solar sails have been studied for a variety of missions and have the potential to provide cost effective, propellantless propulsion that enables longer on-station operation, increased scientific payload mass fraction, and access to previously inaccessible orbits (e. g., non-Keplerian, high solar latitudes, etc.). Research being conducted by the In-Space Propulsion (ISP) Technologies Projects is at the forefront of NASA's efforts to mature propulsion technologies that will enable or enhance a variety of space science missions. Solar sail propulsion systems will be required to meet the challenge of monitoring and predicting space weather by the Office of Space Science's (OSS) Living with a Star (LWS) program. Near-to-mid-term mission needs include monitoring of solar activity and observations at high solar latitudes.

10:20 AM **Break**

10:40 AM AAS 04-105 Progress and Plans for System Demonstration of a Scalable Square Solar Sail System

D. Murphy, T. Trautt, M. McEachen, M. Eskenazi, D. Messner, G. Laue, and P. Gierow, SRS Technologies

The NASA In-Space Propulsion (ISP) program has recently begun sponsoring extensive development and demonstration activities of solar sail system technology. Significant efforts are underway to design, model, build and test large-scale sail systems. Progress on design definition, analysis developments, performance projections, and plans for ground demonstration of a scalable system are discussed.

11:00 AM AAS 04-107 Solar Sail Geostorm Warning Mission Design

C.L. Yen, JPL

In the solar sail community, a Geostorm monitoring mission is regarded as one of the best choices for the first application of solar sail technology. In a Geostorm monitoring mission, a spacecraft is placed between Sun and Earth so that any harmful solar events (coronal mass ejections) are detected before Earth experiences them. Radio signals sent to earth from the monitoring station provide a warning period, since electronic signals travel faster than solar wind. The closer the location of the monitoring station is to Sun the more warning time is gained. Such a station is required to maintain the Sun-Probe-Earth lineup geometry approximately for the duration of the mission. The maintenance of such an orbit location will entail prohibitive amounts of propellants with rockets, chemical or electric propulsion systems. A solar sailcraft is ideally suited for this purpose because it uses no fuel and simply needs to set the sail to face Sun fully at all times. Practical aspects of designing this mission are discussed in this paper.

Session 2: Orbital Mechanics I

Chair: Bob Glover
AT&T Government Solutions, Inc.

9:00 AM AAS 04-108 A-B-Cs of Sun-Synchronous Orbit Mission Design
Ronald J. Boain, JPL

The sun-synchronous orbit is one of the most frequently used orbits for earth science missions. Generally within the field of astrodynamic and mission analysis, the sun-synchronous orbit is understood to be a near polar orbit where the nodal precession rate is matched to the earth's mean orbital rate around the sun. This has the effect of maintaining the orbit's geometry with respect to the sun nearly fixed such that the sun lighting along the groundtrack remains approximately the same over the mission's duration.

9:20 AM AAS 04-109 The Use of X-ray Pulsars for Spacecraft Navigation
Suneel I. Sheikh and Darryll J. Pines, University of Maryland; Paul S. Ray, Kent S. Wood, Michael N. Lovellette, and Michael T. Wolff, NRL

This paper presents a novel technique for determining spacecraft time, position, velocity, and attitude using celestial X-ray sources, such as pulsars. Pulsars are rapidly rotating neutron stars that generate electromagnetic radiation and appear as unique, periodic, and stable sources. These pulsar signatures can be accurately modeled and their arrivals times predicted. In this paper, an overview of pulsars is presented, along with a brief description of missions, including the NRL USA experiment, used to catalogue and characterize these sources. Additionally, the complete time and position solution is developed to illustrate how X-ray pulsars might be used for 3-D position determination.

9:40 AM AAS 04-110 Optimal Continuous Coverage of the Northern Hemisphere with Elliptical Satellite Constellations
François Dufour, CNES

The design of a satellite constellation is often driven by coverage objectives. Many methods have been developed to evaluate the coverage efficiency of a constellation pattern, but they are often restricted to continuous global coverage analyses of satellites on circular orbits. Unfortunately, a global coverage of the planet is not always the most cost effective paradigm. In many cases, it is better to optimize a constellation according to zonal coverage objectives rather than a global one. Moreover, to further improve the zonal coverage of the satellites, we should switch to elliptical orbits to allow the satellites to stay for a longer time in view of the zonal targets around their apogee. In this paper, we will show that with some modifications we can still use Walker's coverage analysis method based on satellite triplets to assess the coverage efficiency of satellite constellation patterns on elliptical orbits. As an illustration of the method, we will present the best patterns to cover the Northern hemisphere with symmetrical constellation very similar to the Walker constellations. To limit the search domain, but also because of their remarkable stability, we will use only elliptical orbits with a frozen perigee.

10:00 AM AAS 04-111 Precise Specialised Orbit Insertion and Maintenance for Small Earth-Observation Satellites
Manop Aorpimai, Small Satellite Research Centre, Thailand; and Phil L. Palmer, Surrey Space Centre, UK

In this paper, we investigate the precise conditions for the specialised orbits which are useful for Earth-observation satellites, namely the resonant condition for repeat-groundtrack orbit and the frozen condition for minimum altitude variation orbit. The analysis is based upon a redundant set of orbital elements called epicycle elements. As well as avoiding circular orbit singularity, our analytical analysis allows higher geopotential harmonics to be included up to an arbitrary number until a satisfactory accuracy has been achieved. We can precisely evaluate the specialised conditions with a simple and instructive mathematical description. In the second part of the paper, we propose firing strategies to optimally insert the satellite from any initial condition towards specialised conditions. We concentrate on a small single burn strategy which is preferable for small satellites whose onboard and ground station facilities are limited. We also propose an autonomous maintenance strategy to keep the satellite at the resonant condition despite perturbations from atmospheric drag. Finally, we show the experimental results obtained from a 300-kg satellite. Both the orbit insertion and orbit maintenance demonstrations confirm the performance of the proposed strategies.

10:20 AM Break

10:40 AM AAS 04-112 Recent Developments in the Models Used for Orbiter Lifetime Analysis
Mark A. Vincent, Raytheon

Two new atmospheric models were designed for propagating medium-altitude Mars satellites. They both correspond to a single molecular species which has a scale height that varies with altitude and temperature (each model in a different manner for the latter) as opposed to the standard of having multiple species each having scale heights as a function of temperature only. The formulae developed for the models were then also used to extrapolate a standard Earth atmosphere model to higher altitudes for a decommissioning study. Also included is an update on the previously published Trinomial Method used for handling the uncertainty in modeling multiple solar flux cycles.

11:00 AM AAS 04-113 Optimal Constellation Design for Orbital Munitions Delivery System
Jason Anderson and Steven G. Tragesser, Air Force Institute of Technology

A constellation of space maneuver vehicles (SMV) could carry munitions payloads to any point on the Earth. The SMV is a lifting body capable of controlled atmospheric reentry. This paper explores the dynamics of atmospheric reentry, establishes a nominal constellation of SMVs, and finally focuses on using genetic algorithm (GA) techniques to determine the minimum number of SMVs required to guarantee munitions delivery to any point on the Earth within 90 minutes.

11:20 AM AAS 04-114 CALIPSO's Mission Design: Sun Glint Avoidance Strategies
Laurie M. Mailhe and Conrad Schiff, a.i.. solutions, Inc.; and John H. Stadler, NASA Langley Research Center

CALIPSO will fly in formation with the Aqua spacecraft to obtain a coincident image of a portion of the Aqua/MODIS swath. Since MODIS pixels suffering Sun glint degradation are not processed, it is essential that CALIPSO only co-image the glint free portion of the MODIS instrument swath. This paper presents Sun glint avoidance strategies for the CALIPSO mission. First, we introduce the Aqua Sun glint geometry and its relation to the CALIPSO-AQUA formation flying parameters. Then, we detail our implementation of the Sun glint computation in FreeFlyer and perform a cross-track trade space analysis. Finally, we analyze the impact of the Sun glint avoidance strategy on the spacecraft power and delta-V budget over the mission lifetime.

Monday, February 9, 9:00 AM — Haku

Session 3: Special Session: ACS Sensor Alignment and Calibration

Chair: Mark Pittelkau
Applied Physics Laboratory

9:00 AM **AAS 04-115** **Unscented Kalman Filtering for Spacecraft Attitude State and Parameter Estimation**
Matthew C. VanDyke, Jana L. Schwartz, and Christopher D. Hall, Virginia Polytechnic Institute

An Unscented Kalman Filter (UKF) is derived in an attempt to solve the spacecraft dual estimation problem with greater accuracy than is attainable with an Extended Kalman Filter. The EKF is an extension of the linear Kalman Filter for nonlinear systems. Although the EKF has been used successfully in many nonlinear applications, the performance is limited, due mostly to the truncation of all but first-order terms. The UKF is able to achieve greater estimation performance than the EKF through the use of the unscented transformation, which allows it to capture first and second order terms of the nonlinear system.

9:20 AM **AAS 04-116** **Attitude Determination and Calibration with Redundant Gyros**
Mark E. Pittelkau, Applied Physics Laboratory

A calibration filter is developed for redundant-axis inertial measurement units (RIMUs), which have more than three sense axes. It is shown that a linear combination of the calibration parameters is not observable in attitude and therefore cannot be estimated by updating a Kalman filter with only attitude measurements. This is a geometric observability problem and is not related to dynamic observability. Calibration maneuvers are required for dynamic observability but do not affect the geometric observability. A null-space measurement equation, together with an attitude measurement model, provides complete observability so that all calibration parameters can be estimated. Estimator performance without and with the null-space measurement update is demonstrated via simulation results.

9:40 AM **AAS 04-117** **Generic Procedure for Modeling Skewed Multiple-Axis Gyros**
Peter Lai, Northrop Grumman Space Technology

A generic procedure was developed to model any skewed multiple-axis gyros. The development starts with the definition of each gyro axis. Instead of defining the misalignments in the X, Y, and Z axis as done before, two misalignments per gyro axis are defined in the spherical coordinates. The clean form formulations for any skewed gyro with up to unlimited number of axes were then derived. This procedure can further differentiate the rotational and non-orthogonal misalignments, which are critical in some scenarios. A skewed 4-axis gyro in the EOS-AQUA satellite is used as an example to demonstrate the easy implementation of this generic procedure.

10:00 AM **AAS 04-118** **ICESAT GLAS Precision Attitude Determination for Early Laser Operation**
S. Bae, R. Ricklefs, B. Schutz, S. Yoon, and C. Webb, The University of Texas at Austin

The Geoscience Laser Altimeter System (GLAS) was launched on ICESat in January 2003. Precision attitude determination (PAD) of the GLAS optical bench during the early mission was accomplished using two star trackers and a hemispherical resonator gyro (HRG). The PAD was accomplished with one of the star trackers and the HRG, but the second camera, known as the LRS, provided some unique information. The performance of the PAD methodology, based on the Extended Kalman Filter, shows 2 arc-sec RMS with respect to the classical QUEST algorithm, but the accuracy of this early result is limited by thermal variations observed by the LRS.

10:20 AM **Break**

10:40 AM AAS 04-119 Autonomous Focal Plane Calibration Using Intelligent Radial Basis Function Networks

Puneet Singla, D. Todd Griffith, Kamesh Subbarao, and John L. Junkins, Texas A&M University

In this paper, a novel real time focal plane calibration algorithm is presented using a Radial Basis Function Network. The algorithm proposed in the paper is inherently sequential in nature and therefore can be used recursively in real-time to update the calibration coefficients. The network architecture in addition to the network parameters is adapted in contrast to simply adjusting weights in a fixed architecture network. The efficacy of the algorithm is validated by introducing different kinds of unknown distortions in the simulated star images.

11:00 AM AAS 04-120 Attitude and Interlock Angle Estimation for GIFTS Mission

Puneet Singla, D. Todd Griffith, and John L. Junkins, Texas A&M University

An efficient Kalman filter based algorithm has been proposed for the spacecraft attitude estimation problem for EO-3 GIFTS using split field of view star camera and 3 axis rate gyros. The conventional spacecraft attitude algorithm has been modified for on-orbit estimation of interlock angles between two FOV's, gyro axis and spacecraft body frame. The real time estimation of the interlock angles will make it robust to thermal and environmental effects unlike in ground estimation.

11:20 AM AAS 04-121 Star Tracker Calibration and Attitude Control System Validation for Demeter Satellite

Jean Mignot, Jean-Marc Julio, and Michel Le Du, Centre National D'Etudes Spatiales, France

Myriade is a microsatellite concept initiated by CNES, designed to produce several spacecrafts for different purposes. DEMETER is the first microsatellite of the product line that will use for Attitude and Orbit Control System (AOCS) the Danish Technical University (DTU) Star tracker as the main sensor for the operational normal mode. This paper presents results of the first validation performed for AOCS verification and validation using real avionics equipments and real DTU Star Tracker in the loop paired with a satellite simulation provided by the Satellite System Validation Test Bench (BVSS).

11:40 AM AAS 04-122 System Identification of a Spherical Air-Bearing Spacecraft Simulator

Jana Schwartz and Christopher D. Hall, Virginia Polytechnic Institute

Virginia Tech has developed a testbed comprised of two independent spherical air-bearing platforms for formation-flying attitude control simulation, the Distributed Spacecraft Attitude Control System Simulator. The DSACSS is intended to support a wide range of functions. As such, requiring that all controllers be robust to approximations of the system parameters is impractical. We document the development of batch and sequential system identification techniques for the full, nonlinear equations of motion of the system. We compare the performance of these techniques in several simulations and provide the results obtained from their application on the experimental system.

Monday, February 9, 9:00 AM Maile

Session 4: Special Session: Space Surveillance Processing

Chair: Mike Stringer
Air Force Space Commmand

9:00 AM **AAS 04-123** **NORAD/USSTRATCOM Systems Certification Process**
Heather L. Morgenstern, USAF Strategic Command

Systems certification is a formal declaration through an independent process that a mission string, system, or element of the warning and attack assessment system satisfies system integrity [illegible] This paper will explain [illegible] SSTRATCOM System [illegible] and scope of systems certification, introduce the certification process, and present current Space Surveillance Network asset certification issues.

LATE WITHDRAWAL

9:20 AM **AAS 04-124** **AFSPC Astrodynamic Standard Software**
Denise Kaya, Nancy Ericson, and Major Donald Davis, AFSPC Space Analysis Division and AFSPC Space Situational Awareness Branch

AFSPC developed Astrodynamic Standard Software to emulate the operational astrodynamic algorithms used by the Space Control Center (SCC) in the Cheyenne Mountain Operations Center (CMOC). This was done to help ensure interoperability, reduce future software development and sustainment costs, and provide the ability to more easily upgrade the SCC algorithms. With the advent of the Integrated Space Command and Control (ISC2) contract, AFSPC is establishing one set of astrodynamic standards within the SCC that will be the same standards that are used by AFSPC customers that use or provide SCC data products.

9:40 AM **AAS 04-125** **DOD Laser Clearing House - Policy and Implementation**
Robert Morris, AFSPC Space Analysis Division; and Steven Gabriel, SI International

The Department of Defense (DOD) is concerned that a laser experiment could inadvertently illuminate a satellite and cause damage to the satellite. To minimize the possibility of damage by DOD lasers, DOD has established procedures to ensure safe and responsible laser activities by DOD agencies. The DOD laser operator works with the Laser Clearing House (LCH) which provides deconfliction services to help prevent inadvertent illumination of orbiting satellites. This paper describes the DOD laser safety policy and the implementation of that policy by the Laser Clearing House along with some real world examples involving actual DOD laser users.

10:00 AM **Discussions**

10:20 AM **Break**

10:40 AM **AAS 04-126** **Space Surveillance Network Automated Tasker**
Beth Wilson, 1st Space Control Squadron, AFSPC

The 1st Space Control Squadron (1 SPCS) has the responsibility to task the sensors in the Space Surveillance Network (SSN) to receive positional data on man-made space objects. Prior to 1993, the sensors of the SSN were not given complete direction on which space objects to track. Thus some objects did not receive enough data to update their element sets, while others had a surplus. In order to maximize the utilization of the Space Surveillance Network, an automated tasker was developed and operationally employed. This program is accomplished daily and provides each sensor in the SSN a list of satellites they are to collect positional data on, the amount of data required and relative priority of the objects. This paper will give a background of SSN tasking, review how 1 SPCS manages the automated tasker and some limitations of this program.

11:00 AM AAS 04-127 Tools and Databases used to Maintain the Space Catalog at 1 CACS
Michael E. Stringer and Bob Teets, 1st Space Control Squadron, AFSPC

One of the 1st Space Control Squadron's (1 SPCS) missions is to maintain the most accurate satellite catalog of Earth orbiting objects. In order to perform this mission 1 SPCS has developed tools to analyze the over 96 million historical element sets (elsets) on our mission support system. This paper will describe some of the tools and databases that have been developed. These tools will be demonstrated for correlating unknown objects to known launches or determining if something has happened to a known object or if these are objects that have never been previously tracked.

11:20 AM AAS 04-128 How Space Surveillance Contributed to the STS 107 Accident Investigation
T.S. Kelso, R.F. Morris, G.T. DeVere, J.C. Randolph, B.R. Bowman, R.A. Racca and N.L. Ericson, Air Force Space Command; and R.G. Thurston, 1 SPCS/DOMA, Air Force Space Command

This paper addresses the analyses conducted by the AFSPC Space Analysis Center in support of the Columbia accident investigation. The analyses covered a range of space surveillance issues—from examining the breakup of a rocket body during the STS 107 mission, reviewing results of the recent NASA debris campaign, and assessing a "close approach" reported by the crew on Flight Day 5. Most notably, this paper will show how the Flight Day 2 piece was discovered and analyzed to determine its ballistic and radar characteristics and how this effort helped NASA determine whether this piece was from Columbia and, if so, what it might have been.

11:40 AM Discussions

Monday, February 9, 1:30 PM Haku

Session 5: Interplanetary Missions I

Chair: Jean de Lafontaine
Université de Sherbrooke

1:30 PM AAS 04-129 Angle-of-attack-modulated Terminal Point Control for Neptune Aerocapture
Eric Queen, NASA Langley Research Center

An aerocapture guidance algorithm based on a calculus of variations approach is developed, using angle of attack as the primary control variable. Bank angle is used as a secondary control to alleviate angle of attack extremes and to control inclination. The guidance equations are derived in detail. The controller has very small onboard computational requirements and is robust to atmospheric and aerodynamic dispersions. The algorithm is applied to aerocapture at Neptune. Three versions of the controller are considered with varying angle of attack authority. The three versions of the controller are evaluated using Monte Carlo simulations with expected dispersions.

1:50 PM AAS 04-130 Design of Lunar Gravity-Assist for the BepiColombo Mission to Mercury
Stefano Campagnola, European Space Agency; Carlos Corral Van Damme, GMV; and Rüdiger Jehn, European Space Agency

The BepiColombo mission to Mercury makes use of a lunar gravity-assist to increase the payload mass into the final orbit. The swing-by of the Moon is carefully designed in order to gain the highest escape velocity in the suitable direction, taking into account the launcher performances. Furthermore a phasing loops strategy is investigated, which extends the 11 days launch window up to some 30 days and eventually to 140 days. The effect of the lunar perturbation is studied and a set of trajectories is integrated. Finally, the maneuvers to correct for the launcher dispersion are estimated.

2:10 PM AAS 04-131 Nozomi Earth Swingby Orbit Determination
Mark Ryne and Sumita Nandi, JPL

The Nozomi mission has been disrupted by several anomalies, including a maneuver under burn, loss of the low gain S-band transponder and a large solar flare which damaged many spacecraft systems. These anomalies dictate that Nozomi operate in an orientation that precludes the collection of Doppler tracking data and severely degrades other types of navigation data. Large navigation errors would have resulted in the loss of scientific return from the mission. This paper describes the Jet Propulsion Laboratory effort to navigate Nozomi, in conjunction with Japan's Institute of Space and Astronautical Science, past two Earth swingbys using differential tracking techniques to successfully place the spacecraft on a trajectory reaching Mars in December 2003.

2:30 PM AAS 04-132 End-to-End Mission Analysis for a Low-Cost, Two-Spacecraft Mission to Europa
Michael Khan and Stefano Campagnola, ESA/ESOC

In-depth mission analysis of a low-cost mission to the Jupiter moon Europa is presented. This involves a Europa orbiter and a relay spacecraft, launched by a single Soyuz-Fregat launcher. The analysis covers the entire project from launch to end of mission. An efficient Venus-Earth-Earth gravity assist transfer with launch in 2009 is found. The transfer and launch technique allow up to 1600 kg of initial payload mass. Separate radiation optimized tours in the Jupiter system are designed for each spacecraft. Finally, the actual two-month science phase is analyzed.

2:50 PM **AAS 04-133** **Evaluation of an Energy-Cuto Algorithm for the Saturn Orbit Insertion Burn of the Cassini-Huygens Mission**
Troy Goodson, JPL

The Cassini-Huygens spacecraft was launched on October 15, 1997 as a joint NASA/ESA mission to explore Saturn. After a 7-year cruise the spacecraft will enter orbit around Saturn on 1 July 2004 for a 4-year investigation of the Saturnian system. This paper describes the navigation-related aspects and analysis of the burn cut-o algorithm for the orbit-insertion burn. The algorithm is designed to achieve the desired orbital period in spite of possible burn delays and restarts.

3:10 PM **Break**

3:30 PM **AAS 04-134** **1-AU Calibration Activities for Stardust Earth Return**
Brian M. Kennedy, Eric Carranza, and Kenneth E. Williams, JPL

In January of 2006, the Stardust spacecraft will deliver a Sample Return Capsule to the recovery sight in northern Utah. Stardust will return dust samples from comet Wild 2 collected in January 2004, as well as interstellar dust collected at earlier epochs in heliocentric orbit. During Earth return, the trajectory will be perturbed by small firings of the spacecraft reaction control thrusters. Calibration of such activities is essential to ensure meeting Earth entry requirements. This paper will describe such calibrations performed between superior conjunctions in June-July 2003 when Stardust was about 1 AU from the Sun.

3:50 PM **AAS 04-135** **Geometric Analysis of Visibility of Mission Support Infrastructure for Phobos and Deimos Utilization**
William J. Chadwick III, David B. Spencer, and Robert G. Melton, The Pennsylvania State University

A high-precision navigation system to support robotic and human missions to Mars in the next 20 to 30 years could be greatly enhanced by the development of an architecture that uses the Martian moons. Placing navigational beacons or communications stations on the moons, whose positions can be determined from Earth with relatively high accuracy, would provide the necessary reference points for a more extensive Mars Positioning System. This study examines one of the issues associated with this concept – the visibility of systems placed on one of the moons from the Earth and the sun. A geometric analysis is performed, and a comparison is made with Analytical Graphics' Satellite Tool Kit software. The results of this examination showed that the moons are viable options for communications relays and navigation beacons. The analytical analysis showed that the sides of Phobos and Deimos facing Mars have a maximum visibility with Earth 38.93% and 45.67% of the time, respectively, and the sides of the moons that lead the orbital path of Phobos and Deimos have maximum visibilities with Earth.

4:10 PM **AAS 04-136** **New Horizons Pluto Approach Navigation**
James K. Miller and Dale Stanbridge, Kinetx Inc.

The navigation of the New Horizons spacecraft during approach to Pluto and its satellite Charon is described. The great distance of the spacecraft from the Earth and Sun presents several new challenges that are identified and described by analytic formula. The two-body dynamics present a particularly interesting problem of satellite orbit determination. A complete covariance analysis is performed describing navigation and science data acquisition accuracies. The results of the covariance analysis are compared with analytic formula to provide insight into the operation of the navigation system.

4:30 PM AAS 04-137 Options for Optimal Trajectory Design of a Mission to NEOs Using Low-Thrust Propulsion

Mauro Massari and Franco Bernelli-Zazzera, Politecnico di Milano

This paper deals with the refinement process of optimal trajectories for missions that use low-thrust propulsion, that were found using a direct transcription method with multi-phase approach. Two different options are considered to refine the trajectories. The first option considers the decay of performances of the engine, with the distance from sun, in terms of specific impulse and thrust. The second considers the case of constant thrust, and is obtained by splitting each original phase accordingly with the switching scheme found in the original solution. A mission to NEOs has been considered to show the steps of the process.

Monday, February 9, 1:30 PM Pikake

Session 6: Attitude Dynamics & Control I

Chair: Don Mackison
University of Colorado

1:30 PM AAS 04-138 Time-Varying Potential Function Control for Constrained Attitude Tracking
Massimo Casasco and Gianmarco Radice, University of Glasgow

The problem of autonomous constrained attitude tracking within the context of potential function control is addressed. Two different attitude representations (using quaternions and modified Rodrigues parameters) are considered. The control systems takes action in order to reach the minimum of a time-varying Lyapunov potential function that accounts for current attitude, target attitude and any pointing constraints, which may be present. This method proves to be successful in forcing the spacecraft to track the desired attitude while avoiding the pointing constraints. Finally advantages and drawbacks of both attitude representations are discussed.

1:50 PM AAS 04-139 Trimmability and Maneuverability Analysis of the Unmanned Space Vehicle
Andrea Guidi, Massimiliano Pastena, and Michelangelo Serpico, Italian Aerospace Research Center

The objective of this document is to define, in the Longitudinal Symmetric flight condition, the aerodynamic trim parameters, the field of manoeuverability and the static stability for the FTB 1 configuration of the Unmanned Space Vehicle (USV) in different locations of the Center of Mass (COM). The study was executed in order to analyze the behavior of the USV vehicle. A rectangular area of investigation was selected as the possible area of movement for the CoM. For each of these points, the trimmability analysis was executed in order to be able to extrapolate the behavior of the vehicle with respect to the variation in the CoM location. The analyses were performed using MATLAB routines.

2:10 PM AAS 04-140 Attitude and Position Estimation from Vector Observations
Daniele Mortari, J. Maurice Rojas, and John L. Junkins, Texas A&M University

This paper present two different approaches to solve the 6-DOF navigation problem by estimating attitude and position using a set of n vector line of sight measurements. The first approach is a novel non-iterative Linear Algebra Resection Approach that provides a rigorous linearization of the problem, if six or more beacons are available. The solution is provided in a single-point geometric fashion, analogous to the now-classical solutions of the Wahba problem. The second approach is based on two mathematical ideas and greatly simplifies the nonlinearity of the problem. Once the problem is rewritten in terms of the three position variables only then, via a multivariate resultant calculation, it is reduced to a single polynomial of degree 8 in just one position variable. This is solved by an efficient hybrid algorithm that combines the classical Cauchy residue theorem with Newton's method. Once the position is found then the attitude is evaluated with ESOQ-2, the fastest optimal attitude determination algorithm.

2:30 PM **AAS 04-141** **Spacecraft Attitude Estimation from Vector Observations Using a Fast Particle Filter**
Yaakov Oshman and Avishy Carmi, Israel Institute of Technology

A new particle filtering algorithm is presented for the estimation of spacecraft attitude quaternion from vector observations. The filter is implemented in the case of a low Earth orbit spacecraft, acquiring noisy geomagnetic field measurements via a three-axis magnetometer. Innovative enhancements render the new estimator highly efficient and enable its implementation with a remarkably small number of particles. Moreover, the quaternion's unit norm is naturally maintained, requiring no ad hoc modifications. An extensive simulation study is used to demonstrate the new filter's performance and to compare it with the conventional extended Kalman filter and the unscented Kalman filter.

2:50 PM **AAS 04-144** **Attitude Determination and Control of a Nanosatellite Using Only the Geomagnetic Field**
Phill-Sun Hur, Robert G. Melton, and David B. Spencer, The Pennsylvania State University

This paper describes an application of control law to reorient a spin axis of a spin-stabilized satellite in an intermediate inclined orbit, using two magnetic torque rods for reorientation and spin rate independently. A simple control law that changes polarity of the rod to generated desired torque is applied, using the angular momentum vector as the basis for the error function. Attitude determination will be done with a 3D-magnetometer-only method and using an extended Kalman filter. No gyro instrument will be used. Because the attitude sensor is a magnetometer, no sensing can be possible while applying the magnetic torque rods, and attitude correction due to the control moment from magnetic torque rods will be derived with only prediction of angular velocities. This research shows an optimal control sequence between measurements and control impulses. Application of this method to Penn State University's nanosatellite LionSat is presented.

3:10 PM **Break**

3:30 PM **AAS 04-143** **Spatial Structure of Attitude Uncertainty**
Sergei Tanygin and Vincent Coppola, Analytical Graphics, Inc.

An important aspect of attitude determination is covariance analysis. It can be essential for precise and robust instrument pointing, target acquisition and communications. As part of this analysis, covariance visualization can be a powerful tool directly illustrating the spatial structure of the uncertainty. While covariance visualization of position naturally produces ellipsoids in three-dimensional space, covariance visualization of attitude is not as straightforward. Various attitude error parameterizations and corresponding covariance definitions have been introduced for attitude determination in both single-frame and filter configurations. None produce ellipsoids that can be easily interpreted in a three dimensional vector space.

3:50 PM **AAS 04-142** **Flexible Space System States and Parameters Estimation**
Adriana Trigolo, Luiz Carlos Gadelha de Souza, and Helio Koiti Kuga, National Institute for Space Research - INPE

This paper presents the results from a study of elastic displacement, damping and frequency estimation using the Kalman Filter methodology. A flexible Euler-Bernoulli beam, connected to a rigid core with torques as input and angles and angular velocities as outputs is used as simple mathematical model of a rigid-flexible satellite to apply the Kalman filter identification algorithm proposed. The Kalman filter is tested under several conditions considering cold start with coarse initial knowledge and varied measurement noise levels. At the end comments are drawn about the robustness of the proposed procedure and feasibility of implementation within the control system loop.

4:10 PM AAS 04-145 Equal Chord Attitude Determination Method for Spinning Spacecraft
Jozef C. Van Der Ha

The paper describes the 'Equal Chord Method', which determines the spin axis attitude orientation of a spinning spacecraft using sensor data collected at only one point during the Earth sensor coverage interval, namely at the time when the chord-angles measured by the two pencil-beams are equal. The Earth aspect angle follows directly from the measured equal chord angle. The operational software implementation is very straightforward. The method delivers the correct attitude solution without any a priori knowledge and is insensitive to uniform bias errors in the infra-red Earth radius. The application of the Equal Chord Method is demonstrated using actual sensor data collected by the CONTOUR spacecraft during its six weeks of Earth phasing orbits.

Session 7: Optimization and Control I

Chair: Dan Scheeres
University of Michigan

1:30 PM **AAS 04-146** **Construction of Idealized Free-Return Earth-Mars Cyclers using Minimax Optimization and Combinatorics**
Ryan Russell and Cesar Ocampo, The University of Texas at Austin

A new technique is developed to identify and optimize families of free-return Earth-Mars cyclers. Previous techniques that use solutions of the multiple-revolution Lambert problem are expanded. The entire solution space is investigated for combinations of generic and nPi free-return transfers for cyclers with periods up to three synodic periods. Multiple options for the short Earth-Mars and Mars-Earth legs that characterize the cyclers are included. The generalized technique requires the solutions for thousands of mini-max optimization problems, and results in many promising ballistic Earth-Mars cyclers, most of which are previously undocumented.

1:50 PM **AAS 04-147** **A Quadrature Discretization Method for Solving Optimal Control Problems**
Paul Williams, RMIT University

This paper presents a quadrature discretization method for solving optimal control problems. The quadrature discretization method is a direct collocation approach based on pseudospectral methods. Traditional pseudospectral methods are based on a class of orthogonal polynomials from the Jacobi family, such as Legendre or Chebyshev polynomials, which are orthogonal with respect to a specific weight function over a fixed interval. While these methods have many advantages, the location of the grid points are more or less fixed. The quadrature discretization method allows a much more flexible selection of grid points by the arbitrary selection of the orthogonal weight function and interval. The general approach is outlined and numerical comparisons are performed for different selections of weight functions. It is shown through numerical studies that the Legendre points do not necessarily give the most efficient or accurate solutions.

2:10 PM **AAS 04-148** **An Embedded Function Tool for Modeling and Simulating Estimation Problems in Aerospace Engineering**
Todd Griffith and James Turner, Texas A&M University

An automatic differentiation-based embedded function tool, OCEA (Object Oriented Coordinate Embedding Method), is presented for solving common estimation problems in Aerospace Engineering. The orbit determination and aircraft parameter estimation problems have been chosen as examples. OCEA is extremely useful for computing nth order partial derivatives of scalar, vector, matrix, and higher dimension tensor functions for these applications. Both applications consider algorithm performance and robustness issues associated with applying high order generalizations of the classical first-order optimization and estimation algorithms. OCEA-based tools are expected to have broad applicability for Aerospace problems in particular and engineering problems in general.

2:30 PM AAS 04-149 A Study on the Guidance Correcting Law for the Aerodynamic Ascent Flight
Takayuki Yamamoto, University of Tokyo; and Jun'ichiro Kawaguchi, The Institute of Space and Astronautical Science (ISAS), Japan

As the authors reported, the optimal steering for the vehicles like a spaceplane shows oscillatory behavior. In the case of more complicated and proper equations of motion, it is difficult to solve two-point boundary value problem on the on-board computer. In this paper, we propose new guidance scheme using the approximate expression of the dynamics derived from the result of the optimal steering. Adopting this method, the guidance scheme with only a few parameters is easily obtained and can keep maximizing the terminal horizontal speed by the consumption of a few percentage fuel margins.

2:50 PM AAS 04-150 Optimization of Stationkeeping for a Libration Point Mission
Samantha Infeld and Walter Murray, Stanford University

Missions about the location of the unstable Sun-Earth L2 point will be increasingly complex because of additional mechanical and scheduling constraints. Satisfying such constraints may be viewed as an optimization problem. It adds little further complexity to minimize fuel usage. The formulation of such an optimization problem is explained, and the resulting solutions for simply constrained trials are shown. The formulations are discretized dynamically with DIDO and then solved with a sequential quadratic programming algorithm, SNOPT. The family of optimization problems presented will be developed into optimization capability for more realistically modeled and highly constrained libration-point mission design.

3:10 PM Break

3:30 PM AAS 04-151 Adaptive Pulse-Width-Modulation
Fabio Curti and Maurizio Parisse, University of Rome "La Sapienza"

Many spacecraft attitude control systems use actuators that operate in on-off mode; typical examples are the jet thrusters, for which the control amplitude cannot be modulated. Moreover, if we want to reduce the complexity of the devices that drive the actuators, as for example in the case of magnetic coils, the on-off input is the simplest signal to be generated. The control strategy, presented in this present paper, consists of Pulse-Width-Modulation control according to a reference system adaptive control law that minimizes a cost function. The cost function is a suitable Lyapunov function, which takes into account the state and control variables of the controlled and reference systems.

3:50 PM AAS 04-153 Design of an Optimal Combination of Feedback Control and Iterative Learning Control
Kanji Takanishi and Minh Q. Phan, Dartmouth College; and Richard W. Longman, Columbia University

This paper describes how an optimal learning controller can be designed to work with a feedback controller so that the combination of feedback and iterative learning control is optimal. Optimality is defined as minimizing a cost function that dictates how the tracking error is reduced from cycle to cycle or repetition to repetition. This combination strategy leverages the inherent advantage of feedback control to handle unexpected disturbance and noises, and the advantage of iterative learning control to correct for any error that the feedback controller fails to eliminate, and any unknown repetitive disturbance that may be present in the system.

4:10 PM AAS 04-154 Dynamic Output Feedback Predictive Controllers for Vibration Suppression and Periodic Disturbance Rejection
Richard Darling and Minh Q. Phan, Dartmouth College

A new method to design predictive controllers that provide vibration suppression and periodic disturbance rejection for flexible structures with multiple sensors and actuators is presented. The controller gains are synthesized directly from excitation input and disturbance corrupted output data, requiring neither knowledge of a system model nor the disturbance frequencies. This design is an improvement over a previous design method in that the order of the controller can now be specified regardless of the duration of the receding-horizon cost function. Thus the controller can be kept "low order" whereas the duration of the cost function remains large to ensure asymptotic stability.

4:30 PM AAS 04-155 Dynamic Response of a System Driven by Thermal Actuation
Maurizio Parisse and Fabio Curti, University of Rome "La Sapienza"

The work investigates about a simple system made of a continuous cantilevered beam with a tip mass, subjected to external loads and actuated by a control system. The beam can be axially tensioned by using a thermal actuation to modify its response to the external disturbances. The axial thermal load is used with a twofold purpose: it simulates the variation of the response characteristics and therefore the impact on the control system which is largely based on the estimate of modes and frequencies. As a technical device, on the other hand, the axial thermal load can be considered a filter; according to the characteristics of the known forcing terms, it is possible to modify the system natural frequencies to minimise undesired effects.

Monday, February 9, 1:30 PM Maile

Session 8: Formation Flying I

Chair: Rao Vadali
Texas A&M University

1:30 PM **AAS 04-157** **Aspherical Formations Near the Libration Points of the Sun-Earth/Moon Ephemeris System**
B.G. Marchand and K.C. Howell, Purdue University

Multi-spacecraft formations, evolving near the vicinity of the libration points of the Sun-Earth/Moon system, have drawn increased interest for a variety of applications. This is particularly true for space based interferometry missions such as TPF and MAXIM. The present study considers both continuous and discrete control methods as applied to non-natural formation configurations. A discrete Floquet controller, previously developed for the determination of natural formations, is further investigated. Its application to inertially fixed formations is of particular interest. Also, continuous output feedback linearization methods (sub-optimal) are similarly employed. The general focus is around multi-spacecraft formations that are constrained to evolve along an aspherical surface, such as a paraboloid, such that the orientation of the formation is fixed in inertial space. The development is presented in the Sun-Earth/Moon ephemeris model.

1:50 PM **AAS 04-158** **Dynamics of Satellite Formations on Eccentric Orbits**
Edwin Wnuk and Justyna Kaczmarek, A. Mickiewicz University, Poland

The paper concerns the theory of the relative satellite motion flying in the formation on orbits with arbitrary values of the eccentricity and takes into account all perturbation effects due to non-spherical geopotential and gravitational influence of the Sun and the Moon. 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. The theory of relative perturbation presented in the paper is the extension of the theory presented in previous papers of the Authors to orbits with high values of the eccentricity. The paper presents also new formulas for the relative satellite motion with any restriction concerning the plane of satellite orbits. The paper contains several numerical results showing good accuracy of the theory and applications to the dynamical analysis of different satellite clusters moving on an arbitrary eccentricity orbits.

2:10 PM **AAS 04-159** **Characterization of the Relative Motion of Rendezvous Between Vehicles in Proximate, Highly Elliptic Orbits**
Carrie Dumas Olsen, NASA Marshall Space Flight Center; and Wallace Fowler, The University of Texas at Austin

This paper deals with rendezvous between two vehicles in highly elliptic orbits with eccentricities between 0.6 and 0.9. Due to the varying orbital speeds of the two vehicles, the relative motion is highly initial condition-dependent and varies significantly from the relative motion seen in circular rendezvous. Relative motion targeting and propagation routines which output relative coordinates in a suitable curvilinear coordinate system are presented. Parametric studies are presented as an initial characterization of the solution space. This solution space is constrained for this and all subsequent investigations by the definition of two types of co-apsidial target/chaser vehicle relationships.

2:30 PM **AAS 04-160** **Centralized and Distributed Formation Flying at Sun-Earth L2 Libration Point**
Gianmarco Radice and Massimo Casasco, University of Glasgow

The coordination and control of a constellation of spacecraft, flying a few meters from one another, dictates several interesting design requirements, including efficient architectures and algorithms for formation acquisition, reorientation and resizing. The spacecraft must perform these transitions without interfering or colliding into each other. Furthermore position keeping is fundamental for ... ave configurations with ... The method hinges on ... tion current attitude, the final target attitude and collision avoidance. A review of the fundamentals of relative motion and dynamics is presented before describing the features of the control algorithm and validating the method using Lyapunov's theorem. Finally, a master-slave and a distributed architecture are compared highlighting the advantages and the drawbacks of both.

LATE WITHDRAWAL

2:50 PM **AAS 04-161** **Control of Libration Point Satellite Formations**
S.R. Vadali, H. Bae, and K. T. Alfriend, Texas A&M University

As a part of the Origins program, NASA is planning to support many missions requiring distributed space-based interferometry. One of the common elements of the proposed missions is formation flying of multiple sub-apertures distributed around a collector, which will follow a periodic (Halo) or quasi-periodic (Lissajous) trajectory around the trans-terrestrial libration point (L2). This paper discusses the construction of specific relative orbits between two satellites near L2 and presents fuel requirement budgets. Control laws for formation maintenance, reconfiguration, and slewing using the input feedback linearization technique are also presented for a model distributed Fizeau interferometer problem.

3:10 PM **Break**

3:30 PM **AAS 04-162** **The Development of High Fidelity Linearized J2 Models for Satellite Formation Flying Control**
Jennifer Roberts and Peter Roberts, Cranfield University

The inclusion of the linearized J2 effect in the Hill equations of relative motion gives greater insight into the formation dynamics and the opportunity to investigate alternative feedback control strategies for the station keeping of a formation of satellites. Time varying and analytical models are developed to incorporate the J2 perturbation and its effects on the relative motion of two or more satellites in LEO. Analysis is performed in detail to determine the best modelling strategy for satellite formation keeping in the J2 perturbed environment. LQR control laws are designed and performance evaluated for the time varying and analytical J2 models and the basic Hill equations using Matlab/Simulink and the Satellite Tool Kit.

3:50 PM **AAS 04-163** **Development of a State Transition Matrix for Relative Motion using the Unit Sphere Approach**
Hui Yan, Prasenjit Sengupta, Srinivas R. Vadali, and Kyle T. Alfriend, Texas A&M University

A relative motion state transition matrix (STM) based upon Hill's equations are insufficient for long-term prediction, due to the assumptions of spherical Earth, circular reference orbit, and linearized gravity model. The STM developed by Gim and Alfriend incorporates 1st order J2 and eccentricity effects in the equations but with the assumption of small relative orbital differences. In this paper, we use the unit sphere method to obtain the exact kinematic description for relative positions and develop a more accurate STM useful for long term relative motion propagation and control design.

4:10 PM AAS 04-152 Criteria for Best Configuration and Sub-Optimal Reconfiguration for MMS Mission

Dong-Woo Gim and Kyle T. Alfriend, Texas A&M University

The magnetospheric multiscale (MMS) mission requires various kinds of highly eccentric reference orbits, a tetrahedron configuration for the formation, and the reconfigurations of the formation for the different measurements under the existence of the perturbation. Since the geometric method gives a precise analytic solution for the relative motion without the limitation on eccentricity and without the singularity, it is applied to the mission with the primary gravitational perturbation J2. The configuration is set up in terms of differential orbital elements and the best one is selected among several candidates by the criteria such as quality factor, interest factor, drift factor, risk factor, and fuel factor. Using the closed form state transition matrix by the geometric method, this best configuration is propagated and the formation is reconfigured to have the desired configuration at the desired time by the sub-optimal two-impulse orbit transfer.

Tuesday, February 10, 8:30 AM Haku

Session 9: Tether Satellite Systems

Chair: Peter Bainum
Howard University

8:30 AM **AAS 04-164** **Probability of Detecting a Tethered Satellite System**

Nammi Jo Choe, Jung Hyun Jo, and John E. Cochran, Jr., Auburn University

In a previous study, the detection of a vertically aligned tethered satellite system was performed by estimating the value of an assumed tether force per unit relative distance between all possible pairs of the observed satellites. In this study, the problem of determining the probability of detecting a tethered satellite system in real time basis is addressed. Vertically aligned two-satellite, three-satellite system, triangular, and tetrahedron configurations are considered. The probability of detecting a tethered satellite system based on range, azimuth and elevation depends upon the observation duration and the magnitude of the tether tension.

8:50 AM **AAS 04-165** **Identification of a Tethered Satellite Using a Kalman Filter**

D.A. Cicci, E.J. Volovecky, and C. Qualls, Auburn University

A Kalman filter has been developed for the state estimation and identification of a tethered satellite which is not known a priori to be part of a tethered satellite system. This filter possesses improved capabilities over previously developed batch filters since it is better able to analyze the libration of the tethered satellite system. Results obtained using the Kalman filter are presented for cases of differing tether lengths, tether orientations, and types of observations being processed. These results are compared to those obtained using a batch filter and conclusions and recommendations on the use of this Kalman filter are provided.

9:10 AM **AAS 04-166** **Command Generation for Tether Retrieval**

Michael Robertson and William Singhose, Georgia Institute of Technology

This paper describes the implementation of the command generation technique called input shaping to the retrieval of tethered satellite systems. The system is described by a simple 2D model and a Lyapunov-based feedback controller is used to control the tethered satellite. This control scheme provides adequate retrieval time; however, combining command generation and feedback control can lead to the reduction of tether retrieval time. Combining command generation and feedback control can lead to the reduction of tether retrieval time. Controller gains can be selected for fast retrieval, while the input shaper can be designed to reduce the magnitude of the unwanted swing angle oscillations.

9:30 AM **AAS 04-167** **Relative Equilibrium of Electro-dynamic Tethers in Equatorial Orbits**

Kalyan Mankala and Sunil K. Agrawal, University of Delaware; and Peter Hagedorn, Technische Universität Darmstadt

In this paper, we look at relative equilibrium of inextensible and extensible tethers attached to a satellite, rotating around the earth in the equatorial plane. The magnetic field of the earth is modeled as a non-tilted dipole. The satellite is assumed as a point mass moving in circular or elliptic orbits. The model development of the tether follows a systematic incremental procedure: a single pendulum, a double pendulum, an inextensible tether, and an extensible tether. For each of the models, the relative equilibrium are characterized numerically, and wherever possible analytically. Stability of the equilibrium configurations is also analyzed. For e.g. a single pendulum model showed a maximum of four equilibrium configurations. In general, the actual number of equilibrium configurations depends on the system variables such as mass, length and resistance of the tether.

9:50 AM **AAS 04-168** **A Low-Cost Mission for Testing In-Orbit a Passive Electro-Dynamic Tether De-Orbiting System**

P. Tortora, Università di Bologna; L. Somenzi and L. Iess, Università di Roma "la Sapienza"; and R. Licata, Alenia Spazio S.p.A.

The need to limit the population of artificial debris in the near-Earth space motivates the development of efficient de-orbiting propulsion systems. Electro-dynamic tethers offer a valid and attractive alternative to conventional chemical thrusters since they impose a penalty in terms of de-orbiting time rather than additional launch mass. We have designed a low-cost demonstration mission, where a reduced-scale de-orbiting system will be carried, deployed and controlled by a microsatellite. Numerical simulations show that this micro system is able to de-orbit a LEO carrier spacecraft in about 2 months, demonstrating salient features of tether technologies and associated electro-dynamic effects.

10:10 AM **Break**

10:30 AM **AAS 04-169** **Guidance and Control of Tethered Satellite Systems using Pseudospectral Methods**

Paul Williams, RMIT University

This paper presents a strategy for implementing a guidance and control system for tethered satellite systems. The strategy is based on a 2 degree of freedom approach where an outer loop, designed using a quadrature discretization method, is combined with a nonlinear receding horizon tracking controller. The outer loop is updated regularly based on the measured system state and implemented in the system with the receding horizon tracking controller. The computational delay in solving the outer loop problem is taken into consideration. Numerical results are presented for a tether-assisted re-entry mission where it is demonstrated that terminal guidance can be achieved. Comparisons with the case where no outer loop is used show considerable improvement in achieving the terminal state.

10:50 AM **AAS 04-170** **Dynamical Effects of Solar Radiation Pressure on a Spinning Tether System for Interferometry**

Claudio Bombardelli, University of Padova; Enrico C. Lorenzini, Howard-Smithsonian Center for Astrophysics; and Marco Quadrelli, JPL

The solar radiation pressure is a key perturbation for high-pointing-accuracy systems (such as interferometers) flying in low-perturbation orbits. After deriving a general expression for the solar radiation force acting on a cylindrical tether, the equations of motion are computed for a spinning system of three satellites connected by two tether arms. The effects of the solar radiation pressure on the interferometer pointing stability and the oscillatory response of the tether are evaluated for a system flying in a heliocentric orbit. The analysis leads to the conclusion that for nominal conditions the system is stable and the tether vibration amplitudes do not affect significantly the performance of the interferometer.

11:10 AM **AAS 04-171** **Space Tethers as Testbeds for Spacecraft Formation-flying**

Mario L. Cosmo and Enrico C. Lorenzini; Harvard-Smithsonian Center for Astrophysics; and Claudio Bombardelli, University of Padua

We propose the low-cost mission EFFECT (Experiment in Formation Flying and Control with Tethers) to be flown in LEO to test critical technological components for formation flying. Before more ambitious missions are launched, EFFECT's flight will provide valuable data on the performance of low-thrust actuators, navigation algorithms and sensors, and real-time positioning. EFFECT's orbital characteristics have been chosen with the goal of minimizing the effects of environmental perturbations typical of LEO. We have used the high-fidelity numerical code MASTER to analyze the dynamical response of the system and assessed the impact of the tether on both the navigation and control subsystems. Finally we will provide a preliminary design of the system configuration with its mass and geometrical characteristics.

11:30 AM AAS 04-172 Effect of Damping on Planar Spin-Up Dynamics of Artificial-Gravity-Generating Tethered Satellite System

Andre P. Mazzoleni, Texas Christian University; and John H. Hoffman, University of Texas at Dallas

This paper concerns analysis of the attitude dynamics of an artificial-gravity-generating tethered satellite system. Earlier work on this project was performed by treating the two sections of the satellite as point masses which were connected by a massless tether which was assumed to be inextensible and to remain straight throughout the deployment and retrieval process; these studies also neglected the effect of tether damping; the analyses to be presented in this paper will account for the elasticity of the tether and will also examine the effect of tether damping on the dynamics of the system. The studies presented in this paper will consider only planar motion.

Session 10: Collision Avoidance, Debris and Atmospheric Drag

Chair: Bruce R. Bowman
Air Force Space Command

8:30 AM AAS 04-173 A Method for Computing Accurate Daily Atmospheric Density Values from Satellite Drag Data
Bruce R. Bowman, Air Force Space Command; Frank A. Marcos, Hanscom AFB; and Mike Kendra, RADEX Corp.

A method has been developed for computing accurate daily density values based on satellite drag data. A differential orbit correction program using special perturbations orbit integration is used to fit radar and optical observational data. Energy dissipation rates are computed over the observation span using a modified Jacchia density model and the fitted B value. Daily temperature values are then computed from the observed EDR values using the "true" 30-year B value of each satellite. The daily density computation was validated by comparing daily density values computed for the last 30 years for many satellites. The accuracy of the density values was determined from comparisons of geographically overlapping data, with over 8500 pairs of density values used in the comparisons.

8:50 AM AAS 04-174 The Semiannual Thermospheric Density Variation From 1970 to 2002 Between 200-1100 km
Bruce R. Bowman, Air Force Space Command

The goal of this analysis is to characterize the semiannual thermospheric density variation over the last 30 years, covering the height range of 200 to 1100 km. Accurate average daily density values have been obtained on 13 satellites. The semiannual variation has been found to be extremely variable from year to year. It has been found that the July-to-October maximum difference can vary by as much as 100% from one year to the next. A moderate correlation has been found between this maximum difference and yearly global temperature variations.

9:10 AM AAS 04-175 Simultaneous Real-Time Estimation of Atmospheric Density and Ballistic Coefficient
James R. Wright and James Woodburn, Analytical Graphics

Historically, for batch least squares orbit determination of LEOs, a ballistic coefficient estimate has been used to absorb atmospheric density modeling errors, as well as ballistic coefficient modeling errors. Problems:(i) The two effects have not been separated. (ii) These least squares estimates are time-constants, but atmospheric density modeling errors are not time constants. (iii) Atmospheric density modeling errors dominate ballistic coefficient modeling errors. (iv) Batch least squares methods are incapable of presenting results in real time. Solution: I will demonstrate the simultaneous real-time estimation of a LEO spacecraft orbit, and both atmospheric density and ballistic coefficient as time varying functions, from real range tracking data.

9:30 AM **AAS 04-176** **Removal of Arbitrary Discontinuities in Atmospheric Density Modeling**
James R. Wright and Sergei Tanygin, Analytical Graphics

The use of discontinuous KP values in global atmospheric density models prohibits the optimal estimation of atmospheric density. The three-hourly discontinuities in KP are always wrong; i.e., three-hourly discontinuities are never produced by the magnetometer readings from which KP is derived. The three-hourly values in KP are global mean values. This fact can be used for a temporary solution. I propose to derive global spline functions from three-hourly global mean values in KP, constrained to be globally continuous, and constrained to reproduce mean value three-hourly constants, in agreement with the input three-hourly global mean values in KP. These splines will be used in place of discontinuous KP values for input to global atmospheric density reference models. Then atmospheric density correction functions derived will not contain arbitrary three-hourly discontinuities due to those in KP, and the total atmospheric density estimates will be free of arbitrary (non-physical) discontinuities.

9:50 AM **AAS 04-177** **A Comparison Atmospheric Neutral Density Derived from Ultraviolet Airglow Observations and the CHAMP Accelerometer**
A.C. Nicholas, S.E. Thonnard, J.M. Picone, K.F. Dymond, and S.A. Budzien, Naval Research Laboratory; J. Emmert, George Mason University; and 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

LATE WITHDRAWAL

lipse associated with the
pheric density corrections
l density specification is
lerived from accelerometer
data, a data driven atmospheric model, and total density derived from satellite drag.

10:10 AM **Break**

10:30 AM **AAS 04-178** **Drag Coefficient Variability from 200-500 km from the Analysis of 4 Spheres**
Kenneth Moe, Science and Technology Corp.

It has been customary to use the drag coefficient 2.2 for satellites of compact shapes when calculating absolute atmospheric densities. However, in recent years, data from specialized satellites have yielded information on gas-surface interactions, enabling us to calculate drag coefficients up to altitudes of 325 km. We present the results showing the drag coefficients as a function of altitude for four differently shaped satellites. Now that the USAF High Accuracy Satellite Drag Model Program has begun to make precise analyses of the orbital behavior of satellites of many shapes up to 500 km, it has become possible to investigate the variation of drag coefficients at higher altitudes as well.

10:50 AM **AAS 04-179** **Disposing of Objects in Geosynchronous Transfer Orbit by Atmospheric Reentry**
Johnston A. Coil and David K Schmidt, University of Colorado

Orbital debris is a growing problem for spacecraft safety. Defunct spacecraft left in Geosynchronous Transfer Orbit (GTO) present a unique hazard; they are uncontrolled, travel at extreme velocities relative to most active payloads, and remain in orbit for a very long time. A reentry model is developed to dispose of GTO spacecraft using trajectory optimization to determine the minimum thrust and impulse values to reenter a spacecraft over a broad range of ballistic coefficients, start points of the reentry propulsion, and burn durations. Numeric results are analyzed for trends and relationships and examples are provided to show uses of the model for feasibility analyses and design requirements generation. A case study validates the data generated by the reentry model and shows how to adapt the model for use in a wide variety of mission-unique scenarios.

11:10 AM AAS 04-180 Collision of Spacecraft of Various Shape with Debris Particles Assessment
Andrey I. Nazarenko, Space Observation Center, Moscow

One of the basic results of space debris models application is the calculation of cross-sectional area flux (Q) for particles of the different sizes relative to given spacecraft (SC). This quantity means the average collision number for a spherical object with unit cross-section per time unit. In many applied tasks there is a necessity of the estimating collision number for bodies of more complex shape (panel, cylinder, cone, etc.). In this paper the technique of taking into account the shape of SC components for calculating the expected collision number per time unit (a flux) is considered.

11:30 AM AAS 04-181 Effects of Cross Correlated Covariance on Spacecraft Collision Probability
Vincent T. Coppola, James Woodburn, and Dick Hujsak, Analytical Graphics, Inc.

The most widely used computation for computing spacecraft collision probability between two objects utilizes the relative position pdf derived from the relative position covariance. It is usually assumed that the position uncertainties are uncorrelated between the two objects---that is, there is no cross correlation covariance contribution to the relative position covariance. This paper examines the sensitivity of the computed collision probability on non-zero cross correlation. In certain cases, small but physically realistic, cross correlation leads to large variations in collision probability. We will present several examples wherein the cross correlation is computed through the use of a filter which simultaneously estimates the orbits of the two objects.

11:50 AM AAS 04-305 Results and Issues of Atmospheric Density Correction
Vasiliy S. Yurasov, KIA Systems, Moscow; Andrey I. Nazarenko, Space Observation Center, Moscow; Paul J. Cefola, MIT/ Lincoln Laboratory; and Kyle T. Alfriend, Texas A&M University

To improve the position prediction accuracy of low altitude satellites an upper atmosphere monitoring service that uses drag estimates associated with catalogued inactive payloads and debris is proposed. Using the element sets of the numerous available objects that are updated by the space surveillance systems a few times per day in near-real time the construction of operative corrections to the modeled atmosphere density without significant additional costs is possible. Using Two Line Element (TLE) sets as the observational data the effectiveness of this density correction process is evaluated by comparison of the orbit determination and prediction results obtained with and without the estimated density variations for several hundred LEO space objects.

Tuesday, February 10, 8:30 AM Pikake

Session 11: Attitude Dynamics & Control II

Chair: Richard Longman
Columbia University

8:30 AM **AAS 04-182** **Application of the Cayley Form to General Spacecraft Motion**
Andrew J. Sinclair and John E. Hurtado, Texas A&M University

The study of N-dimensional rigid body motion is a well developed field of mechanics. Some of the key results for describing the kinematics of these bodies come from the Cayley transform and the Cayley transform kinematic relationship. Additionally, several forms of the equations of motion for these bodies have been developed by various derivations. Using Cayley kinematics the motion of general Lagrangian systems can be intimately related to the motion of higher-dimensional rigid bodies. An example of this is the representation of general orbital and attitude motion of a spacecraft as pure rotation of a four-dimensional rigid body.

8:50 AM **AAS 04-183** **Effects of Internal Mass Flow on the Attitude Dynamics of Variable Mass Systems**
T. Tran, Lockheed-Martin Space Systems; and Jeerapa Sookgaew and Fidelis Eke, University of California

The fluid products of combustion that result from propellant burn in rocket-type variable mass systems can take on helical or whirling motion as they exit the system. This fact is normally ignored in the study of the dynamics of variable mass systems. This paper assesses the difference that proper accounting of such helical motion of fluid particles can make on the attitude dynamics of rocket systems. Results obtained show that internal fluid whirling motion can cause appreciable deviations in spin rate predictions, and also affects the frequencies of the transverse angular velocity components.

9:10 AM **AAS 04-184** **Globally Stabilizing Saturated Attitude Control in the Presence of Bounded Unknown Disturbances**
Robert Wallsgrove and Maruthi R. Akella, The University of Texas at Austin

In this study an attitude-regulating control law is derived on which known limits on the control authority of the system are rigorously enforced. Unknown disturbance torques, assumed to be of lesser magnitude than the control limits, are included in the formulation. Lyapunov analysis is employed to ensure global stability. A smooth control signal containing hyperbolic tangent functions is derived that drives the angular velocity and attitude errors toward zero over a specified time interval of arbitrary length. Asymptotic convergence to a residual set of arbitrarily small measure is guaranteed and demonstrated in simulation. The derived control law is independent of the inertia matrix and therefore robust to inertia parameter uncertainties.

9:30 AM **AAS 04-185** **Influence of Propellant Burn Pattern on the Attitude Dynamics of a Spinning Rocket**
Jeerapa Sookgaew and Fidelis Eke, University of California

This study uses a relatively complex model to study the effect of various propellant burn geometries on the attitude motions of a rocket-type variable mass system. The four burn scenarios studied are the end burn, the radial burn, the uniform burn, and the centripetal burn. Results obtained do indeed show that a change in burn scenario changes the predicted attitude motion. The differences are more pronounced for spin motion than for transverse attitude motion. The end burn is recommended whenever it is practically feasible; it is found to be the least disruptive from the point of view of attitude dynamics.

9:50 AM **AAS 04-186** **Modeling Closely-Coupled Satellite Systems as Quasi-Rigid Bodies**
J. E. Cochran, Jr., H. Aoki, and N. J. Choe, Auburn University

Systems of satellites that include tethered systems and formations are modeled as quasi-rigid bodies in which the relative motions of the satellites are constrained, but not necessarily required to be zero. Both nonlinear and linearized models are developed. The constraint forces determined from the system dynamics are considered of particular importance because they must be provided by physical interconnections, such as tethers, or control forces. The characteristics of the rotational motions of the systems about their centers of mass are also discussed.

10:10 AM Break

10:30 AM AAS 04-187 Optimal Results for Autonomous Attitude Control Using the Potential Function Method

Massimo Casasco and Gianmarco Radice, University of Glasgow

Local and global optimal results for the problem of autonomous constrained slew manoeuvring of a rigid spacecraft within the context of the potential function method are presented. The method hinges on the definition of Lyapunov potential functions in terms of the attitude parameters representing the current attitude, the goal attitude and any pointing constraints, which may be present. The control system proves to be successful in forcing the spacecraft to achieve the desired attitude and avoiding the pointing constraints while minimising a performance index that is a function of both the system state and the control effort.

10:50 AM AAS 04-189 Using Root Locus Departure Angle Compensators to Raise the Cutoff Frequency in Repetitive Control

Chun-Ping Lo and Richard W. Longman, Columbia University

Spacecraft often have vibrations due to slight imbalance in a momentum wheel, or to imbalance in a cryo pump, and this can adversely affect the performance of fine pointing equipment. Repetitive control can learn how to isolate the equipment from spacecraft vibrations. Stability of repetitive control systems requires relatively accurate knowledge of the system for all frequencies. Parasitic poles or residual modes will nearly always result in instability unless the learning is cut off before reaching frequencies for which the model is uncertain. Starting from any chosen design, this paper develops methods of designing a compensator to account for unmodelled dynamics based on the frequency content of the error signal as the error grows. The approach makes use of a library of compensators developed based on root locus departure angle behavior.

11:10 AM AAS 04-190 How to Avoid Singularity for Euler Angle Set?

Puneet Singla, Daniele Mortari, and John L. Junkins, Texas A&M University

In this paper, we will present an algorithm to avoid singularity associated with famous minimum element attitude parameterization, Euler angle set. The proposed algorithm will make use of method of sequential rotation to avoid singularity associated with Euler angle set. Further, a switching algorithm is also proposed to switch between Euler angle set to avoid the singularity while integrating the kinematic equations corresponding to Euler angles for spacecraft motion. The algorithm will be validated by test cases which will describe the worst case motion for a spacecraft.

Tuesday, February 10, 8:30 AM Maile

Session 12**:** Special Session: Optical Satellite Tracking Systems

Chair: Chris Sabol
Air Force Research Laboratory

8:30 AM **AAS 04-191** **Accuracy Assessment of MSSS Metric Data**

Bob Shishido, Bob Brem, Peter Konohia, Chris Sabol, and K. Kim Luu, Air Force Maui Optical and Supercomputing Site

The Maui Space Surveillance System (MSSS) has multiple assets capable of providing highly accurate angular observations of missiles and satellites including the 3.6m AEOS, 1.6m, 1.2m MOTIF, 0.8m BDT, and Raven 0.4m telescopes. This combination provides the MSSS with 24-hr tracking capability and the ability to track satellites in all orbit regimes. This paper provides an accuracy assessment of these tracking assets by comparing observations to external reference orbits. The results show that MSSS metric data are of very high quality with some telescopes approaching the one arcsecond accuracy level.

8:50 AM **AAS 04-192** **The Dynamic Properties of Rotation and Optical Characteristics of Space Debris at Geostationary Orbit**

Y.S. Karavaev, M.N. Mishina, and P.G. Papushev, Institute of Solar-Terrestrial Physics, Russia; and G.S. Mishin, R.M. Kopyatkevich, and N.P. Shaburov, Central Research Institute of Machine Building, Russia

Information about geostationary spacecraft that have ceased their lifetime can be derived from optical observations. Optical observations make it possible to determine the parameters of motion (orbit), as well as the frequency spectrum of observed brightness changes. All observed objects of space debris have a brightness variability in the range of periods from a few seconds to several minutes. Frequency spectra have not yet been studied in detail. In this paper, based on an extensive, long-term data set, we investigate the light curves of space debris at geostationary orbit. A description is given of the equipment for obtaining light curves of moving space objects with high temporal resolution. A study is made of the dependence of rotation periods on design characteristics of the objects observed, and an analysis is made of the variations of periods depending on the observing epoch and the age of the object. A physical interpretation of the observed variations is given, and the long-term influence of space factors on optical characteristics of space debris is estimated.

9:10 AM **AAS 04-193** **Wide Field of View Telescope Development at AMOS**

Bryan Law, Paul Sydney, John Africano, Tom Kelecy, Dan O'Connell, Ed Walker, Chris Sabol, and Paul Kervin, Air Force Maui Optical and Supercomputing Site

The Air Force Maui Optical and Supercomputing (AMOS) site has refurbished a Baker-Nunn telescope, called Phoenix, resulting in a 6.8x6.8 degree field of view optical sensor. AMOS is also developing a 5x5 degree field of view Raven-class telescope and designing a Meter Class Acquisition Telescope (MCAT) in support of NASA's space debris program. These sensors will produce observations of similar quality to many of today's space surveillance sensors while providing greatly improved search and survey capability. This paper presents results of space surveillance experiments with the Phoenix telescope as well as overviews of the WFOV Raven and MCAT development.

9:30 AM **AAS 04-194** **Daylight Astrometry and Design Studies for the LEO Raven**
Capt. Joel Nelson, Air Force Institute of Technology; Paul Sydney, Dan O'Connell, David Talent, Ed Walker, and Chris Sabol, Air Force Maui Optical and Supercomputing Site; and Maj. Matthew Goda, Air Force Institute of Technology

Raven is an award-winning optical system design paradigm that couples commercially available hardware and software along with custom data analysis and control software to produce low-cost, autonomous, and very capable space surveillance systems. The key to these systems is the use of astrometric techniques for position and brightness data. Efforts are now underway to produce a system capable of tracking low Earth orbiting (LEO) satellites: the LEO Raven. This paper presents the results of risk-reduction daylight astrometry experiments using Maui Space Surveillance Site assets and engineering studies to assist in the design and capability projection of the LEO Raven.

9:50 AM **AAS 04-195** **Relative Orbit Determination of Geosynchronous Satellites Using the COWPOKE Equations**
Chris Sabol, Air Force Maui Optical and Supercomputing Site; Keric Hill, University of Colorado; Craig McLaughlin, University of North Dakota; K. Kim Luu, Air Force Maui Optical and Supercomputing Site; and Michael M. Murai, Oceanit Laboratories, Inc.

Optical satellite tracking often reveals multiple satellites in a single telescope field of view. The Cluster Orbits With Perturbations Of Keplerian Elements (COWPOKE) equations are used to estimate the relative motion of geosynchronous satellites and determine if the satellites can be later identified based solely on relative position. This paper provides the development of the COWPOKE equations for modeling the relative motion of geosynchronous satellites and analysis demonstrating the feasibility of using these techniques for object correlation. Real data relative orbit determination results are provided using the optical tracking assets of the Air Force Maui Optical and Supercomputing (AMOS) site.

10:10 AM **Break**

10:30 AM **AAS 04-196** **Canadian Surveillance of Space Concept Demonstrator – The First First 4 Months of Testing**
Lauchie Scott, Frank Pinkney, Brad Wallace, James Rody, Sylvie Buteau, and Martin Levesque, DRDC, Canada; and Bryce Bennett, Royal Military College, Canada

The Canadian Department of National Defense is developing a satellite program designed to perform the task of Space Surveillance on orbit (SAPPHIRE). As a part of the risk reduction measures for SAPPHIRE, a chain of 3 low-cost remote observatories based on the Raven platform was constructed. This paper summarizes the pointing, timing, metric accuracy and throughput testing of the two nearly completed eastern observatories running in manual operation mode. Expectations for the automated observatory performance are presented based on the experiences with these observatories running in manual mode.

10:50 AM **AAS 04-197** **Comparison of Optical and Radar Tracking for Catalog Maintenance**
Kyle T. Alfriend, Texas A&M University; and Chris Sabol and K. Kim Luu, Air Force Maui Optical and Supercomputing Site

The low cost of optical systems, coupled with their capability to operate autonomously and to see low altitude satellites during the day make them a potential valuable asset for assisting in the catalog maintenance of low altitude satellites. In this paper a comparison is made of radar and optical systems for providing updates of the orbital elements for catalog maintenance. First, an analytic model assuming a circular orbit with a sensor on a non-rotating Earth is developed and comparisons made between radar and optical systems. Then, simulations using GTDS are performed and compared with the analytic results.

11:10 AM **AAS 04-198** **High Accuracy Orbit Updates Using Angles-Only Data**
Chris Sabol and K. Kim Luu, Air Force Maui Optical and Supercomputing Site; and Kyle T. Alfriend, Texas A&M University

Accuracy assessment results have shown that Maui Space Surveillance Site (MSSS) metric data are of very high quality with some telescopes approaching the one arcsecond accuracy level. One arcsecond maps into 5m of 1-D position knowledge at a range of 1000 km; therefore, high accuracy angular observation data are highly effective in removing cross-track and along-track errors from low Earth orbit predictions. This paper presents real data results showing that orbit prediction errors can be reduced from the kilometer level to tens of meters using one or two passes of high accuracy optical data and sequential estimation techniques.

Session 13: Optimization and Control II

Chair: Alan Lovell
Air Force Research Laboratory

1:30 PM **AAS 04-199** **Stabilization of Learning Control in the Presence of Parasitic Poles for Short Time Trajectories**
Kenneth Chen and Richard W. Longman, Columbia University

Iterative learning control (ILC) creates controllers that learn from experience with a specific command, aiming for zero tracking error. There are spacecraft applications in which one wants to maneuver or scan with fine pointing equipment and eliminate pointing errors due to flexibility of the vehicle. The simplest form of ILC converges to zero error for nearly all systems for small enough gain, but the transients can be outrageously unacceptable. ILC laws that use knowledge of the system to address this problem can create an unstable learning process when there are residual modes. For long trajectories this can be fixed using a frequency cutoff. This paper addresses the problem for short trajectories. An adaptive approach is developed when no cutoff is to be used. And when a finite time equivalent of a frequency cutoff is used, an adaptive method is developed to eliminate accumulation of error in the unaddressed part of the error space.

1:50 PM **AAS 04-200** **Stability and Performance Analysis of Matched Basis Function Repetitive Control in Frequency Domain**
Masaki Nagashima and Richard W. Longman, Columbia University

Fine pointing device on spacecraft often encounter periodic disturbances from slight imbalance in a momentum wheel or a cryo pump, etc. Matched basis function repetitive control can theoretically eliminate the influence of such disturbances. In comparison to other types of repetitive control, this approach can handle multiple unrelated frequencies. The governing equations are linear with periodic coefficients. In a previous work the frequency raising technique was used to develop equivalent linear time invariant models. Here these time invariant versions of the controllers are studied and compared to other comb filter approaches. Stability analysis methods are developed. And additional averaging methods are investigated aiming to create more ideal disturbance rejection behavior.

2:10 PM **AAS 04-201** **Real-Time Optimization for Optimal Feedback Control of Robot Arms**
Jie Zhao, Columbia University; Moritz Diehl, University of Heidelberg; Richard W. Longman, Columbia University; and Hans Georg Bock and Johannes Schloeder, University of Heidelberg

In previous work by the authors and co-workers, open loop time optimal trajectories for elbow, polar, and SCARA robots were determined, and optimal robot paths were developed for satellite mounted robots to minimize disturbance to the microgravity environment of the satellite. In practical applications one would like to have a method of doing feedback control, and doing so in such a way that the feedback commands perform an optimal trajectory from any measured perturbed state. This paper studies the use of nonlinear model predictive control and investigates the ability to make real-time optimization for feedback corrections. In addition, issues of converting from the objective of reaching the desired endpoint, to the objective of staying there without vibrations is considered.

2:30 PM **AAS 04-202** **Passivity-Based Stable Pi-Like Control Structures for a Class of Nonlinear Systems**

Kamesh Subbarao, The University of Texas at Arlington; and Maruthi R. Akella, The University of Texas at Austin

A novel passivity-based framework for designing stable proportional + integral feedback control structures using limited state information is presented. The control methodology is applied to the spacecraft docking problem, subject to constant and bounded unmodeled disturbances. In particular, we assume that the body angular velocity vector is unavailable for feedback control purposes. The novelty of our control solution lies in the fact that we rigorously avoid the construction and utilization of any dirty derivative type approximations for the spacecraft angular velocity. In contrast, we utilize only the attitude (position) measurement signals and their integrals obtained through appropriately designed low-pass stable filters. Finally, we perform a representative set of numerical simulations to illustrate the performance of this new control algorithm.

2:50 PM **AAS 04-203** **The Evolution of Optimal Trajectories by Implicit Simulation**

John Riehl and Waldy Sjauw, Glenn Research Center; and Stephen W. Paris, Rocky Nelson, and John Hensley, The Boeing Company

Since its inception in 1985 the Optimal Trajectories by Implicit Simulation (OTIS) program has continually evolved. The original release of OTIS focused on endoatmospheric trajectory optimization while recent upgrades have focused on its orbital and interplanetary trajectory capabilities. This continual expansion of capabilities in OTIS coupled with advances in computers
l trajectory optimization
OTIS. These include:
LATE WITHDRAWAL
e definition philosophy,
efinements and auxiliary
programs. Since 1995, NASA Glenn Research Center has maintained and directed the addition of new capabilities into OTIS. Among these new capabilities is OTIS' ability to perform low thrust trajectory optimization. The authors include a comparison of OTIS low thrust capabilities and results to JPL's de facto two-body standard, Varitop, an indirect method optimal control program.

3:10 PM **Break**

3:30 PM **AAS 04-204** **POST Trajectory Convergence Acceleration Using Multiple Shooting**

Ben Raiszadeh, NASA Langley Research Center; and Hans Seywald, Analytical Mechanics Associates

trajectory targeting and
LATE WITHDRAWAL
e shooting method makes
to the initial guesses is
reduced, and convergence is obtained faster.

3:50 PM **AAS 04-205** **Passive Thermal Control of a Spacecraft: A Criterion for the Optmization of Thermo-Optical Parameters**

Maurizio Parisse and Fabio Curti, University of Rome "La Sapienza"

The passive thermal control technique, if usable, is to be preferred for its simplicity, reliability and relative inexpensiveness. The availability of materials and devices is such as to enable the designer to select those with the thermo-optical parameters most suitable for the definition of the on board
choice of absorptivity,
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be the result of general
ses a simple architecture
whose discretization leads to a fair number of thermal balance equations, which, once linearised, are only function of the thermo-optical parameters. A very simple optimal criterion is then applied to select the suitable numerical values to adopt.

4:10 PM **AAS 04-207** **Primer Vector Theory for Optimal Relative Waypoint Flying**

Aaron J. Trask and Alan S. Hope, Naval Research Laboratory

A technique is developed to generate optimal trajectories between waypoints relative to a reference spacecraft. Primer vector theory is applied to develop optimal trajectories between waypoints which are defined in the Hill-Clohessy-Wiltshire relative coordinate system. Impulsive example trajectories are examined for an inspection vehicle.

Tuesday, February 10, 1:30 PM Plumeria

Session 14: Orbital Mechanics II

Chair: Chris Hall
Virginia Polytechnic Institute and State University

1:30 PM **AAS 04-208** **Constellation Design Using Flower Constellations**
Matthew P. Wilkins and Daniele Mortari, Texas A&M University

This paper introduces techniques that can be used to design constellations of satellites using Flower Constellations. Flower Constellations (FCs) are characterized by an axis of symmetry that can be arbitrarily oriented. When the FC axis of symmetry is aligned with the Earth spin axis, then the satellites will have identical repeat ground tracks. FCs are identified by eight parameters: the number of petals Np, the number of sidereal days to repeat the ground track (Nd), the number of satellites (Ns), two phasing parameters (Fn and Fd), and three orbit parameters (w, i, and the perigee altitude, hp). Each of these parameters has a unique effect on the overall design of a FC. This paper discusses some broad categories of constellations and how specific choices of these parameters will generate them.

1:50 PM **AAS 04-209** **Drag Sail Dynamics for EOL Deorbit**
Peter Roberts, Cranfield University, UK

The feasibility of deployable drag enhancement sails is considered for EOL removal of LEO spacecraft, and how they fulfill NASA deorbit guidelines is demonstrated. The concept is a Kapton membrane supported by tape spring struts. A pyramidal geometry is chosen taking advantage of a small damping effect due to motion through the Newtonian flow. Simplified equations of motion are presented. Software is being developed so the reverse flow case can be analysed, demonstrating that dynamically stable sails provide a mass efficient solution as a large surface area at all incidence angles is unnecessary. A demonstrator will be flown from a sounding rocket.

2:10 PM **AAS 04-210** **Effects of Orbit Perturbations on a Class of Earth Orbiting Interferometric Observatories**
Islam I. Hussein and Daniel J. Scheeres, University of Michigan

This paper revisits a class of Earth-orbiting interferometric observatories introduced previously and reviews the general procedures to achieve wave-number plane coverage. The effect of eccentric spacecraft trajectories and other force perturbations on wavenumber plane coverage are considered. Conditions for complete wave-number plane coverage are found for certain classes of orbit perturbations. This analysis leads to design criteria for interferometric observatories that ensure wave-number plane coverage as a function of perturbation strength.

2:30 PM **AAS 04-211** **Large Payloads to LEO Using Endo-Atmospheric Energy Exchange**
Preston H. Carter II, DARPA Tactical Technology Office; and Jason M. Tardy, CENTRA Technology, Inc.

The question of how to achieve reliable, low-cost access to space has challenged the aerospace community for decades. Several proposed successors to the Space Shuttle, such as the National Aerospace Plane and the X-33 have proven technologically unfeasible, too costly, or both. As an alternative, the authors propose a multistage system based on a hypersonic air-breathing aerospace vehicle platform and a conventional rocket. This system, a large-scale evolutionary extension of DARPA's RASCAL micro-satellite space launch program, would combine the responsiveness of an aircraft with the heavy lift capability of a conventional expendable launch vehicle. Such an approach provides the potential for a cost-effective launch system utilizing near-term technology solutions.

2:50 PM **AAS 04-212** **Mission Analysis for the Deorbitation of Spot-1**
Corinne Salcedo, CNES

The SPOT-1 satellite has been launched in 1986. The satellite was dedicated to earth observation. At this time, it has been designed for a lifetime of tree years. Even some recorder failures, the satellite has been operated since last year. Nevertheless last year, the solar generator began a slow degradation. The human space activity generates a major quantity of debris that will pollute the space for centuries if nothing is done. What would happen with SPOT-1 if we let it die on orbit? After the death of SPOT-1 not only the Spot orbit will be polluted but also the surrounding orbits. As a consequence, the decision of decommissioning Spot-1 has been taken at the end of year 2002. This paper presents the mission analysis for the SPOT-1 decommissioning selecting a safety solution to avoid creating more debris and that will allow a reentry of the satellite within 25 years.

3:10 PM **Break**

3:30 PM **AAS 04-213** **Relative Motion Dynamics About a Periodic Orbit**
William E. Wiesel, Air Force Institute of Technology

The local linear coordinate frame introduced by Floquet theory near a periodic orbit is extended into the nonlinear regime. A transformation of variables is forced to be periodic, canonical, and we further insist that it decouple the equations of motion. Solution methods for the decoupling transform are discussed in the non-degenerate and degenerate cases, and results are given to the fourth order. This method identifies zero relative drift manifolds about a periodic orbit, enabling stable formation flight.

3:50 PM **AAS 04-214** **6-DOF Aerobraking Trajectory Reconstruction by Use of Inertial Measurement Unit (IMU) Data for the Improvement of Aerobraking Navigation**
Moriba K. Jah and Michael E. Lisano, JPL

For interplanetary missions, radiometric data is used as a means of determining both the position and velocity of a spacecraft. This requires the DSN and spacecraft to maintain communication lock, which is not continuous throughout aerobraking, specifically while the spacecraft is within the atmosphere. Some spacecraft are equipped with an Inertial Measurement Unit (IMU). The IMU provides information about the spacecraft's non-conservative acceleration and angular motion. Since the spacecraft loses lock during the drag pass, this research focuses upon the use of the IMU data (collected during the radiometric data gap) as a means of augmenting aerobraking navigation capabilities.

4:10 PM **AAS 04-206** **Partially Passive Inclination Control of Geosynchronous Satellites**
Mary K. Johnson and Huntington W. Small, Lockheed Martin Space Systems Company

Geosynchronous satellite orbits with maximum inclination limits of several degrees may or may not require delta-V expenditure to control orbit inclination, depending on the mission lifetime. If the lifetime is short enough, then the inclination can be controlled "passively" (that is, without using fuel) by choosing initial orbit plane parameters properly. For longer lifetimes, a "partially-passive" inclination control approach has been developed. This approach entails both proper initialization of the orbit plane and appropriate cross-track burn planning in order to minimize delta-V requirements. The strategy is described and demonstrated, including results for a variety of mission lifetimes and inclination limits.

4:30 PM **AAS 04-215** **Desensitized Optimal Orbit Insertion**

H. Seywald, Analytical Mechanics Associates

In this paper, the recently introduced concept of Desensitized Optimal Control (DOC) is applied to an optimal orbit insertion problem with model uncertainties. For the sake of simplicity, only atmospheric uncertainties are considered, represented by perturbations in the air density. Along the ascent trajectory, these perturbations are assumed to be arbitrary functions of time of "small" magnitude. The vehicle controls are the throttle setting and the thrust vector angle. In physical terms, the aim is to find ascent trajectories such that i) the nominal fuel consumption is as low as possible, ii) the target orbit is reached precisely as long as the perturbations are zero, and iii) the sensitivity of the achieved target orbit with respect to perturbations in the air density is as low as possible. An optimal trade-off between these conflicting goals is determined with the DOC methodology by minimizing a user-defined cost function involving the overall fuel consumption and the sensitivity of the relevant quantities representing the target orbit with respect to perturbations in the air density.

Session 15: Orbit Determination I

Chair: Felix Hoots
AT&T Government Solutions, Inc.

1:30 PM **AAS 04-216** **Geosynchronous Orbit Determination Using the High Accuracy Network Determination System (HANDS)**

Chris Sabol and Tom Kelecy, Air Force Maui Optical and Supercomputing Site, and Mike Murai, Oceanit Laboratories, Inc.

The High Accuracy Network Determination System (HANDS) is a network of Raven-class telescopes that autonomously track deep-space satellites and provide high accuracy orbit information. Previous works have shown significant geosynchronous orbit determination (OD) improvements are possible using high accuracy angular observations in conjunction with quality ranging data or as the only tracking data source. This paper presents accuracy assessment results of the HANDS optical data and real data orbit determination results for at least two test cases.

1:50 PM **AAS 04-217** **GPS Based Orbit Determination System for the KOMPSAT-2**

Byoung-Sun Lee, Jae-Cheol Yoon, and Jae-Hoon Kim, Electronics and Telecommunications Research Institute (ETRI), Korea

GPS based orbit determination system for the KOMPSAT-2 has been developed. Two types of orbit determination software such as operational orbit determination and precise orbit determination are designed and implemented. GPS navigation solutions from on-board the satellite are used for the operational orbit determination and raw measurements data such as C/A code pseudo-range and L1 carrier phase for the precise orbit determination. Operational concept, architectural design, software implementation, and performance test are described.

2:10 PM **AAS 04-218** **Improvement of Estimated Orbit by Using Single Differenced GPS Observation Data**

Jung Hyun Jo, Nammi Jo Choe, and John E. Cochran, Jr., Auburn University

In previous papers, 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 and an improvement of a geopotential model in the LBPOD were described. To improve the Global positioning system (GPS) measurement model, single-differenced LEO-GPS pseudo range measurements are used. A pairing method for the single differenced GPS measurements is discussed. 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.

2:30 PM **AAS 04-219** **Modeling the Performance of the Naval Space Surveillance Fence**
Geoff Pierce, Tim Cox, and Felix Hoots, AT&T; Michael Zedd, Bernard Kelm, and Shannon Coffey, NRL; and Hugh Hadley, SRC

The Naval Space Command maintains a catalog of over 10,000 satellites. Because of imperfections in the orbit models, each orbit must be periodically reinitialized to reconcile it with the actual satellite trajectory. More than 100,000 observations are processed daily to determine updated element sets for all satellites. More than half of the total observations are contributed by one resource, the Naval Space Surveillance Fence. The fence was first constructed in 1958 and is nearing the end of sustainability. Currently the Government is considering whether to do a refurbishment to provide service life extension, to completely replace the fence, or to just discontinue its use. In order to assist in this assessment, we have constructed a high fidelity simulation of the fence coupled with the associated orbit catalog maintenance. The simulation has been tested and validated using an element set catalog representative of the real world.

2:50 PM **AAS 04-220** **Orbit Determination Covariance Analysis for Planetary and Interplanetary Missions**
Stéphanie Delavault, CNES

In the framework of the MARS PREMIER Program, CNES has developed a covariance analysis tool named EPERON. Using covariance approach, the performance of orbit determination can be estimated very quickly, taking into account all the uncertainties of the models. This is necessary to define the navigation needs and to assess the robustness of navigation performance. First this tool has been applied on interplanetary trajectories. Results of a complete Earth to Mars navigation study for a 2009 NETLANDER mission are presented, demonstrating the feasibility of this challenging phase of the mission. Some performance results for an earth orbit case are also presented.

3:10 PM **Break**

3:30 PM **AAS 04-221** **Orbit Determination of Stardust from the Annefrank Asteroid Fly-by through the Wild 2 Comet Encounter**
Eric Carranza, Brian Kennedy, Kenneth Williams, and Tung-Han You, JPL

Stardust is a 3-axis stabilized spacecraft that maintains its attitude by firing a pair of its one-sided thrusters. This thruster arrangement causes Stardust to produce unbalanced torques at each thruster firing, which yields an undesired perturbing force and makes navigation a challenge. In addition to this perturbing force, Stardust experiences 2 solar conjunctions during its inbound leg to the Wild 2 encounter, which is another major challenge to overcome. Descriptions of the Stardust mission, the spacecraft trajectory and discussion of the navigation challenges will be provided, as well as discussion of the orbit determination estimation procedure, models and performance accuracies.

3:50 PM **AAS 04-222** **Orbit Determination Strategy Using Single Frequency GPS Data**
Yoola Hwang, Korea Astronomy Observatory; and George H. Born, The University of Colorado

This research presents orbit determination results estimated by various ionospheric error correction techniques for a LEO (Low Earth Orbit) satellite using a single frequency GPS receiver. A scale factor, dependent on altitude, was applied to the ionospheric shell model. The direct-calibration method, DRVID (Differential Range Versus Integrated Doppler), used range differences of group delay and phase advance to compensate for the first order ionospheric error. The fidelity of the orbit solutions was tested by orbit overlaps and differences from dual frequency truth orbits. Analyses showed that the DRVID carrier phase can determine the orbit accuracy below the meter level with a single frequency GPS receiver on the LEO satellite.

4:10 PM AAS 04-223 Orbital Covariance Interpolation
Salvatore Alfano, Analytical Graphics

This work derives an interpolator to determine the intermediate covariance of a space object's position. Two factors are considered in the derivation. The first is that the covariance matrix rotates about the orbit's angular momentum vector, maintaining orientation with respect to the velocity vector. The second is that covariance growth and non-orbit related reorientation can be adequately represented by a matrix that varies linearly with time. These two factors incorporate orbital motion (represented by a rotation matrix) with time-associated covariance growth/reorientation (represented by a secondary matrix) to produce realistic intermediate covariance matrices while precisely matching the given covariance matrices at the start and end of a given time interval. The method is computationally simple, using matrix algebra without eigenvalue or eigenvector determination.

4:30 PM AAS 04-224 Special Perturbations to General Perturbations Extrapolation Differential Corrections in Satellite Catalog Maintenance
David Cappellucci and Rick Johnson, Lockheed Martin Mission Systems

LATE WITHDRAWAL

Recent increases in computing power combined with decreased hardware costs have led to the feasibility of maintaining the entire satellite catalog using special perturbations differential correction techniques. Continued use of general perturbations orbit propagators, such as SGP4 and PPT3, dictate the need for generation of GP compatible element sets for distribution to end users. Historically, GP element sets have been maintained in parallel with SP state vectors by differential … examines the use of the … lement sets from the SP … uality of extrapolation, … e overlap of SP fit span and prediction span will be examined. The results of the study will show that the prediction quality of the resulting GP element sets is comparable in quality to the underlying SP predictions over the time span covered by the extrapolation fit. Concurrent improvements in SP theory, including the use of a dynamically calibrated atmosphere (DCA) and segmented solution for drag (SSB), will result in GP element sets much improved over current operational practices. The study covers a satellite population representative of the entire catalog including satellites in multi-day orbits.

Session 16: Interplanetary Missions II

Chair: Dennis Byrnes
Jet Propulsion Laboratory

1:30 PM **AAS 04-225** **SIRTF Takes Flight**
Mark Garcia, JPL

In the pre-dawn hours on August 25th, 2003, the Space Infrared Telescope Facility (SIRTF) was launched from Cape Canaveral Air Force Station into a "first of it's kind" solar orbit. The launch aboard the Delta II 7920H was nearly flawless, with the launch vehicle meeting all attitude requirements on the way to injecting the SIRTF Observatory towards the prescribed launch targets. This paper analyzes the "as flown" trajectories of the Observatory, the Delta Second Stage, and the Observatory's Dust Cover, and compares them to pre-launch predicts. Mission design implications of the medium-term (beyond the mission lifetime goal of 62 months) and long-term (for as far out as can reasonably be propagated) solar orbit will be discussed. Trajectory-related software tools and algorithms created in support of Mission Operations, as well as analyses performed to calculate the probability of on-orbit micrometeroid impact, will also be presented.

1:50 PM **AAS 04-226** **Earth Return Maneuver Strategies for Genesis and Stardust**
Kenneth E. Williams, JPL

As part of NASA's Discovery Program, Genesis and Stardust will be the first missions since the Apollo Program to return samples collected in deep space. To constrain costs of recovery, entry requirements must be much tighter than those imposed on Apollo. Spacecraft designs were also greatly simplified to limit costs, giving rise to a variety of operational limitations and constraints. In light of these considerations, approach to Earth presents a challenge in terms of both mission planning and navigation. This paper discusses strategies for trajectory correction during the Earth return phases of both missions.

2:10 PM **AAS 04-227** **Trajectory Design for the Genesis Backup Orbit**
Roby S. Wilson, JPL; and Brian T. Barde, Northrop Grumman Space Technology

In September 2004, the Genesis spacecraft will return to Earth with its collection of solar wind samples. If for some reason there are any difficulties with returning the samples to Earth during the nominal entry sequence, a contingency plan is in place for a second chance at a successful recovery. This paper will detail the processes used to generate this backup trajectory, as well as other contingency options examined through the course of the study. After the sample return capsule separates from the rest of the spacecraft, the remaining portion is still fully functional. It has been proposed to use this very functional spacecraft to continue to study the solar wind, albeit in a different regime than about the libration points. The remainder of the paper will discuss the design of the trajectory for this proposed extended mission.

2:30 PM **AAS 04-228** **WMAP Shadow Avoidance Maneuver Analysis**
Dale R. Fink, CSC; and Steven E. Coyle, NASA

The Wilkinson Microwave Anisotropy Probe (WMAP) satellite, maintained in orbit about L2, would need to avoid Earth and Moon shadows for a possible extended mission. This paper describes the method for predicting the specific probable set of shadows that would occur to WMAP were no Shadow Avoidance Maneuvers (SAM) performed, then shows how these shadows can be avoided through relatively small, appropriately timed maneuvers that adjust the phase of the Lissajous orbit geometry while minimizing impact to the mission science objectives and satisfying all spacecraft health and safety constraints.

2:50 PM **AAS 04-229** **Trajectory Options for a Mars Sample Return Mission**

Lorenzo Casalino and Guido Colasurdo, Dip. Energetica - Politecnico di Torino

The paper discusses several EP-trajectory options to accomplish the heliocentric legs of a Mars sample-return mission and compares the different strategies in terms of time-length and payload delivered to Mars and/or Earth. In particular, direct, Earth-Gravity-Assist (EGA), Mars-Gravity-Assist (MGA), and Earth-Mars-Gravity-Assist (EMGA) trajectories are considered for the outbound leg. Direct and MGA trajectories are considered for the return leg. Attention is paid to the different options that are available for the capture by Mars (electric propulsion, chemical propulsion, or aerobraking), as they greatly influence the mission strategy for the outbound heliocentric leg.

3:10 PM **Break**

3:30 PM **AAS 04-230** **Trajectory Space for a Low Thrust Earth-to-Jupiter Mission**

Kurt J. Hack and Robert D. Falck, NASA Glenn; and Carl G. Sauer and Eugene P. Bonfiglio, JPL

LATE WITHDRAWAL

There have been many studies examining Earth to Jupiter missions using low thrust. This study explores the trade space of a constant low thrust transfer between Earth escape and Jupiter capture as ... The performance of such ... t parameters: the ratio of ...), specific impulse and ... thrust arcs are shown. Comparison of coplanar, circular planetary orbits to actual planetary orbits via ephemerides is shown over several opportunities.

3:50 PM **AAS 04-231** **Finite Burn, Roundtrip Interplanetary Trajectories with ISP Constraints and Mass Discontinuities**

Chris Ranieri and Cesar Ocampo, The University of Texas at Austin

An indirect optimization method is used to compute minimum propellant, roundtrip, time-constrained, finite burn trajectories. Realistic lower and upper bounds on the ISP are included for variable specific impulse engines. Mass discontinuities are considered which account for any mass dropped off or picked up at the target. Finally, the optimal control problem includes a state equality constraint requiring the spacecraft to maintain zero relative position and velocity with the target in addition to matching at the arrival and departure times from the target.

4:10 PM **AAS 04-232** **Optimal Planetary Orbital Transfers via Chemical Engines and Electrical Engines**

A. Miele and T. Wang, Rice University

Because the orbital periods for planetary orbital transfers are of order hours, the primary objective of an optimal trajectory is to minimize the propellant consumption. In this paper, we present a systematic investigation of optimal trajectories for planetary orbital transfer. Major results on thrust control, propellant consumption, and flight time are presented with particular reference to LEO-to-GEO transfer. For both spacecraft powered by chemical engines and spacecraft powered by electrical engines, the results were obtained with the sequential gradient-restoration algorithm for optimal control problems in either single-subarc form or multiple-subarc form.

4:30 PM AAS 04-233 Phobos Imaging and Mapping Preliminary Mission Design

Stefano Casotto and Alessandro Tonello, Università di Padova

The preliminary design of an imaging mission to the Mars moon Phobos has been developed. A review of the scientific and imaging data available from the past missions highlighted the necessity of a new dedicated approach to the study of Phobos. The primary goal of this mission is to completely map the surface of the satellite at high resolution. The project is conceived as the preliminary phase of a main mission to Mars, thus subject to the constraints of a low Delta-V budget and short duration. This study focuses on both the imaging and the associated maneuvering strategy necessary to perform the global mapping with spatial resolution of at least 1.5 m/pixel. The probe will have a near polar, circular orbit around Mars at an orbital altitude close to that of Phobos. Since Phobos has a near equatorial orbit, the probe will execute close fly-bys with the satellite during its nodal crossings. Orbital phasing procedures have been analyzed, as well as the combined effects of the orbital maneuvers and the perturbations due to gravity field of Mars.

Wednesday, February 11, 8:30 AM Haku

Session 17: Orbit Determination II

Chair: Bobby G. Williams
KinetX Inc.

8:30 AM **AAS 04-234** **A Two-Timescale Discretization Scheme for Collocation**
Prasun N. Desai, NASA Langley; and Bruce A. Conway, University of Illinois

This paper describes the development of a two-timescale discretization scheme for Collocation. A larger discretization scheme can be utilized for the smooth varying lower frequency state variables and a second separate finer discretization scheme can be utilized for those state variables having higher frequency dynamics. Consequently, the finer discretization timescale can be tailored to only those state variables that have higher frequency dynamics. This approach allows the size of the overall Nonlinear Programming Problem to be reduced significantly as compared to the standard single timescale Collocation architecture.

8:50 AM **AAS 04-235** **Range Bias Modeling for Satellite Catalog Maintenance**
A. M. Segerman, AT&T Government Solutions, Inc.; and K. A. Akins, Naval Research Laboratory

High-precision orbit determination routines typically account for time-varying range observation biases. They generally accomplish this by treating the range bias during each overhead pass as a fit parameter. Such fitting of range bias parameters, on a pass-by-pass basis, has been added to a satellite catalog maintenance software package, intended for use with large amounts of observational data for many satellites. Statistics are presented, indicating the extent to which this process affects the overall maintenance effort, both in terms of accuracy as well as computation time.

9:10 AM **AAS 04-236** **Autonomous Target Tracking of Small Bodies During Flybys**
Shyam Bhaskaran and Joseph E. Riedel, JPL

Spacecraft flybys of small solar system bodies provide important science return in the form of images of the target body taken around closest approach. In order to maximize the number of images taken of the target, an autonomous closed-loop tracking system has been developed to maintain lock on the target during the flyby. The system uses images to estimate the spacecraft's target-relative position and attitude, which is then used to point the camera. The system has been successfully used twice: the Deep Space 1 flyby of comet Borrelly and the Stardust flyby of asteroid Annefrank. This paper describes in detail the tracking algorithms and flight results.

9:30 AM **AAS 04-238** **A Variable Step Double Integration Multi-Step Integrator**
Matthew Berry, Virginia Tech; and Liam Healy, Naval Research Laboratory

The Gauss-Jackson numerical integrator is a fixed step multi-step integrator. Gauss-Jackson is a double integration integrator; it integrates position directly from acceleration, which reduces round-off error. Gauss-Jackson is derived assuming a constant step-size, so it must be restarted if the step size is changed. The Shampine-Gordon integrator is a variable step, variable order single integration multi-step integrator. Shampine-Gordon is derived with divided differences, so the step size can be changed without restarting the integrator. In this paper we combine the concepts of the Gauss-Jackson and Shampine-Gordon integrators to derive a variable step double integration multi-step integrator.

9:50 AM **AAS 04-239** **Establishment and Validation of the NRL 1-Meter Telescope Position**
Alan Hope, Jay Middour, Joe Simons, and William Scharpf, Naval Research Laboratory; and Mark Davis and John Seago, Honeywell

The Naval Research Laboratory has begun operating a new Satellite Laser Ranging facility near Quantico, Virginia. This paper describes work done to establish the position of the facility with respect to the International Terrestrial Reference Frame. Traditional differential GPS survey techniques and a novel statistical position determination method are discussed. Finally, the end-to-end accuracy of the resulting position and associated calibration procedures is measured by comparing observations from the NRL site to an independent Satellite Laser Ranging system while simultaneously tracking the same satellite.

10:10 AM **Break**

10:30 AM **AAS 04-240** **Examination of NORAD TLE Accuracy using the Iridium Constellation**
William H. Boyce III, Boeing Satellite Operations & Ground Systems

The accuracy of the General Perturbation NORAD TLE data has been the subject of much discussion and speculation. This paper examines the accuracy of the SGP4 element sets published by US Space Command (NORAD TLEs) using tracking data from nine live Iridium satellites. A large database of accurate orbit estimates from the Iridium satellites was available to serve as the truth reference for this analysis. Iridium Orbit Services provides a new orbit estimate at the end of every tracking station contact. Each active Iridium satellite is tracked 10 times per day so there is always plentiful data for a satellite within near the epoch of a NORAD TLE. The Iridium estimates may therefore be used as a basis for judging the accuracy of the NORAD element sets and, by implication, the efficacy of using the NORAD sets for collision avoidance. In terms of the standard deviations of the Iridium data, it is found that the average TLE position error is several tens of sigmas. The utility of such data for collision avoidance planning is discussed.

10:50 AM **AAS 04-241** **Geosynchronous Orbit Determination Using Space Surveillance Network Observations and Improved Radiative Force Modeling – Results of Real Data Processing**
Richard H. Lyon, Zachary J. Folcik, and Paul J. Cefola, Lincoln Laboratory

This study is intended to improve orbit determination accuracy for 3-axis stabilized geosynchronous satellites via an improved radiative force model. The macro-model approach, developed earlier at NASA GSFC for the TDRSS spacecraft, has been adapted for the UNIX version of the Goddard Trajectory Determination System (GTDS) at the MIT Lincoln Laboratory. The capability has been introduced to access this model from both the numerical and semi-analytical orbit generators within GTDS. This paper is an extension of AAS03-523 and describes software development, testing, and real data processing, as well as a macro-model for the NASA Geosynchronous Operational Environmental Satellites (GOES) spacecraft. Additionally, this paper presents the results of tuning this model and improving GOES orbits using observations from the Space Surveillance Network.

11:10 AM **AAS 04-242** **Automatic Generation and Integration of Equations of Motion by Operator Over-Loading Techniques**
D. Todd Griffith, Andrew J. Sinclair, and John E. Hurtado, Texas A&M University; and James D. Turner, AMDYN Systems

This paper presents a new method for the automatic generation and integration of equations of motion using operator overloading techniques. An automatic differentiation tool (OCEA: Object Oriented Coordinate Embedding Method) is utilized to compute the partial derivatives required for implementing the traditional Lagrangian equations of motion. A key advantage of this approach is overcoming the limitations of both the symbolic and numerical multibody modeling and simulation tools. The new method combines the best of the symbolic and numerical equation of motion generation methods, while retaining the simplicity and elegance of the original Lagrangian method. Several examples will be presented to illustrate the method.

Session 18**:** Orbital Mechanics III

Chair: Paul Penzo
Global Aerospace Corporation

8:30 AM **AAS 04-243** **A Simple Algorithm to Compute Hyperbolic Invariant Manifolds Near L1 and L2**
B.F. Villac and D.J. Scheeres, The University of Michigan

The hyperbolic invariant manifolds associated with periodic and quasi-periodic orbits about the libration points L1 and L2 have proven to be a key ingredient in mission design, such as the Genesis mission. However, their computation, generally based on series representations near the libration points, is difficult over long time spans. We propose a simple algorithm to compute these invariant manifolds accurately based on their characterization of in terms of escape and capture trajectories. We apply this algorithm to the spatial Hill three body problem. Using our approach, we also compute homoclinic and heteroclinic connections between periodic orbits in this problem.

8:50 AM **AAS 04-244** **Orbit Mechanics about Planetary Satellites**
M.E. Paskowitz and D.J. and Scheeres, University of Michigan

This paper explores orbit mechanics in the Hill 3-body problem, concentrating on spacecraft motion about Jupiter’s moon Europa. Using an averaging approach with first order corrections, we develop an approximate theory of motion valid over a wide range of initial conditions. Using this theory stable regions of orbital motion at high inclinations are found. Regions where the averaging theory breaks down are characterized numerically and are found to contain families of trajectories that are temporarily captured. We show that these trajectories can be placed into high inclination stable orbits with a sequence of maneuvers.

9:10 AM **AAS 04-245** **An Approach to the Design of Low Energy Interplanetary Transfers Exploiting Invariant Manifolds of the Restricted Three-Body Problem**
Francesco Topputo and Amalia Ercoli Finzi, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano; and Massimiliano Vasile, ESA/ESTEC

In this paper a general algorithm for the design of low energy interplanetary transfers, exploiting invariant manifolds of periodic orbits around libration points, will be presented. The algorithm looks for the best intersection between the invariant manifolds associated to the departure and arrival bodies. The best intersection is chosen according to the value of a merit function associated to Poincaré sections. If an optimal intersection cannot be found, invariant manifolds are linked by solving a Lambert’s problem or through a low-thrust arc and the resulting trajectory is then optimised. In order to have a full 3D representation of the transfer, the algorithm has been integrated with an analytical ephemeris model. Some interplanetary trajectories are presented, showing the effectiveness of the proposed approach.

9:30 AM **AAS 04-246** **Keeping a Spacecraft on the Sun-Earth Line**
Carlos M. Roithmayr, NASA Langley Research Center; and Linda Kay-Bunnell, Analytical Mechanics Associates, Inc.

Measurements of Earth's atmosphere as it occults sunlight can be obtained advantageously from a spacecraft placed in the proximity of the Sun-Earth Lagrange point L2. Maintaining the condition of continuous solar occultation by all parts of the atmospheric disk requires that the displacement of the spacecraft perpendicular to the Sun-Earth line remain less than 200 km. However, the gravitational force exerted on the spacecraft by the Earth's moon must be negated by propulsion in order to meet this rather tight constraint. We provide an estimate of propulsive force needed to keep the spacecraft coincident with L2, and a second estimate in which the spacecraft is allowed to move along the Sun-Earth line.

9:50 AM **AAS 04-247** **Minimum-Fuel Periodic Orbits in the Vicinity of a Fixed Point on the Sun-Earth Line: The Planar Case**
Haijun Shen, Renjith R. Kumar, and Hans Seywald, Analytical Mechanics Associates

Minimum-fuel periodic orbits are obtained for the station-keeping of the L2 gossamer telescope for the RASC (Revolutionary Aerospace Systems Concepts) occultation study mission. It is required that the spacecraft stay at least 1.45 million kilometers away from the earth but within 200 kilometers from the sun-earth line. It is assumed that the earth and moon revolve about the earth-moon barycenter, and the earth-moon barycenter and the sun revolve about the composite barycenter. The inclination of the earth-moon orbital plane with respect to the ecliptic plane is neglected. Minimum-fuel periodic orbits are obtained using the direct method. A candywrap-shaped periodic trajectory is obtained which is different from the traditional orbits around Libration points. These periodic orbits require significantly smaller amount of fuel consumption than holding the spacecraft at the sun-earth L2 point.

10:10 AM **Break**

10:30 AM **AAS 04-248** **LEO Constellation Design Using the Lunar L1 Point**
James Chase, JPL; Naomi Chow, Erica Gralla, and N. Jeremy Kasdin, Princeton University

Over the last decade, there has been a growing interest in the development of low earth orbit (LEO) satellite constellations. Along with several commercial ventures (such as Iridium and Orbcomm), NASA and the Department of Defense have shown interest in using satellite constellations for continuous global coverage. However, a significant problem facing these developers is the high cost of these missions. In particular, since separate launch vehicles are generally required to reach different orbital planes, the cost of multiple launches may represent as much as 40% of the life-cycle cost. Thus, there is a need for new launch trajectories that would reduce the number of launch vehicles needed. This paper presents such a trajectory, which offers significant cost savings for satellite constellations currently being considered. The new trajectory uses a lunar L1 point rendezvous and an Earth-return aerocapture to deliver satellites to multiple orbital planes via a single launch. This trajectory can reduce launch costs by more than 50% for certain types of micro-satellite constellations.

10:50 AM **AAS 04-249** **Analytical Gradients for Trajectories with Long Duration Burns, Coast Segments, and Flybys**
Scott Zimmer, University of Texas at Austin

A procedure for calculating the analytical derivatives required for an indirect optimization method of combined long duration finite burn segments, coast segments, and multiple gravity assist trajectories is presented. Because the control satisfies Pontryagin's maximum principle, the thrust magnitude and spacecraft equations of motion are discontinuous. The analytical derivatives are calculated using the state transition matrix associated with the complete set of the Euler-Lagrange equations of the optimal control problem on each trajectory segment as well as a matrix that maps perturbations across any discontinuities in the spacecraft state or equations of motion.

11:10 AM AAS 04-250 A Tool for the Preliminary Design of Low-Thrust Gravity Assist Trajectories

Paolo De Pascale and Amalia Ercoli Finzi, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano; and Massimiliano Vasile, ESA/ESTEC

The availability of advanced propulsion systems opens doors to a new scenario for future interplanetary missions, requiring powerful preliminary trajectory design tools, capable of efficiently exploring the solution space, locating optimal mission options. In this paper a tool for the preliminary definition of complex interplanetary trajectories is proposed. It can be used to design both multiple gravity assist and low thrust gravity assist trajectories. It is based on a shape-based approach combined with a particular global optimization technique, resulting from a hybridization of evolution programming with deterministic search methods. In the paper the effectiveness of the proposed tool is demonstrated by a number of examples of design of complex interplanetary trajectories characterized by low-thrust, gravity assist maneuvers, or a combination of them.

11:30 AM AAS 04-251 Modeling of Proof Mass Self-Gravity Field for the Laser Interferometry Space Antenna (LISA)

Marco B. Quadrelli, JPL

This paper describes the development of the self-gravity modeling tool used to predict and control the motion of one of the proof masses of the orbiting LISA gravitational wave detector. LISA is a space-borne gravitational wave detector, which is formed by three spacecraft orbiting the Sun and forming the vertices of an equilateral triangle with a side of 5 million km in length. Requirements on the forces and moments, and the force gradients and moment gradients, applied to the proof mass exist. This paper computes these quantities analytically, so that gravitational balancing considerations can now be done effectively.

Session 19: Formation Flying II

Chair: Ron Proulx
Charles Stark Draper Laboratory

8:30 AM **AAS 04-252** **Comparison of a Nominal Versus Relaxed Guidance Algorithm for Formation Reconfiguration of LEO Spacecraft**

T. Alan Lovell, Air Force Research Laboratory; and Steven G. Tragesser, AFIT/ENY

In this paper a multiple-impulse burn maneuver algorithm for relative motion trajectory reconfiguration based on the two-body Hill's equations is reviewed from previous work. This algorithm is then further developed to allow more flexibility in terms of the number and direction of the burns and their location on the trajectory. This relaxed algorithm is then compared to the original, in terms of both fuel efficiency and practicality, for several test cases. The relaxed algorithm is shown to provide several advantages over the nominal, and with a fuel penalty that is normally not substantial.

8:50 AM **AAS 04-253** **A Lyapunov-Based Controller for Satellite Formation Reconfiguration in the Presence of J2 Perturbations**

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

A control law to reconfigure a satellite formation from an initial set of relative orbit parameters, to a desired set of relative orbit parameters, is developed. The control is derived from a candidate Lyapunov function, and is proven to globally and asymptotically stabilize the current orbit with respect to the desired orbit, even in the presence of J2 perturbations. By the use of mean elements in the control law, and by neglecting the differential J2 accelerations, the control law can be simplified considerably with negligible loss in accuracy. Numerical simulations are provided, of formations both with low, and high eccentricity reference orbits.

9:10 AM **AAS 04-254** **Cluster Planning and Control for Spacecraft Formations**

Mark E. Campbell, Darren Zanon, and Jayant Kulkarni, Cornell University

A generalized planning methodology for satellite clusters is presented. The methodology, initially developed for low Earth orbiting clusters of satellites, has been extended to clusters in highly elliptical orbits and in clusters around Earth-Sun Lagrange points; combined control and planning architectures have also been addressed. The methodology utilizes Hamiltonian-Jacobi-Bellman optimality to quickly generate a set of maneuvers from an initial stable formation to a final stable formation. The approach also considers state of the art, low impulse electric propulsion, collision proximity, communications, and distribution/scaling. This paper gives an overview of the general methodology, implementations for each reference orbit, and insights through simulations.

9:30 AM **AAS 04-255** **Interval Control of Formations in Eccentric Orbits**

Ossama Abdelkhalik and Thomas Alberts, Old Dominion University

The problem of controlling a spacecraft formation moving in an eccentric orbit is addressed. In the interest of fuel conservation, it is suggested that the formation station keeping is maintained only in a time interval that covers the target area for the mission and then left to propagate naturally with respect to prescribed initial states. This paper explores controllers that achieve station keeping in the required time interval. Both a linear approach and a nonlinear one are considered. A linear approach is developed using a Lyapunov approach based on the linearized equations of motion. A nonlinear control is developed using an inverse dynamics approach based on Kepler equations. A Simulation tool is developed to evaluate both approaches. The results demonstrate the advantage of using the latter.

9:50 AM **AAS 04-256** **Low Thrust Control Optimization for Satellite Formation**
John S. Seo and William E. Wiesel, Air Force Institute of Technology

An analytic study of body-fixed low-thrust optimal control for a satellite formation is presented. The familiar Clohessy-Wiltshire relative motion model is employed in the minimum-time formulation. The resulting two-point boundary value problem is approached analytically. By the implicit function theorem, a non-singular Jacobian (of partial final state over partial initial co-state) will guarantee a unique and isolated solution. The existence of the solution is now a function of the initial and final state pair. This paper will present the results of this analytical study of feasible initial and final state pair for optimality.

10:10 AM **Break**

10:30 AM **AAS 04-257** **Autonomous Orbit Navigation of Two Spacecraft System Using Relative Line of Sight Vector Measurements**
Jo Ryeong Yim, Korea Aerospace Research Institute; John L. Crassidis, University at Buffalo; and John L. Junkins , Texas A&M University

Autonomous orbit navigation of two spacecraft system is considered with the relative line-of-sight vector measurements between two spacecraft system. Observability of the system with the available measurements is investigated using the linear observability analysis by using the Lie derivatives with respect to the various orbit configurations. Error covariance analysis based on the extended Kalman filter is considered and autonomous orbit navigation is obtained, and the result is conformed through the Monte-Carlo simulation. The estimation results show that the position can be estimated with an accuracy of about 200 m and the velocity about 0.2 m/sec.

10:50 AM **AAS 04-258** **Optimal Trajectory Generation and Control for Reconfiguration Maneuvers of Formation Flying using Low-thrust Propulsion**
Mauro Massari, Roberto Armellin, and Amalia Ercoli Finzi, Politecnico di Milano

In this work the reconfiguration of spacecrafts flying in formation with low-thrust propulsion has been faced. The aim is the development of a control strategy that reduces the propellant use for reconfiguration maneuvers and that can be applied in real time. First a method to generate the optimal trajectory for the entire formation has been developed using a direct approach and a simplified model of the relative dynamics with respect to elliptic reference orbits, then the same method has been applied to control the maneuvers. Finally simulations considering a complete model have been carried on for different kind of reconfigurations.

11:10 AM **AAS 04-259** **Relative Motion Stabilization of a Coulomb Spacecraft Cluster**
Hanspeter Schaub, Virginia Polytechnic Institute

A Coulomb spacecraft is able to exploit inter-spacecraft electrostatic charges to directly control the relative motion. Previous research has demonstrated equilibrium solutions in circular orbits, as well as developed a nonlinear control law for a two satellite formation in circular and elliptic orbits. This paper studies the relative motion stabilizing problem for larger clusters of equal Coulomb spacecraft. Since the motion of a charged craft will affect the motion of all other charged craft in the cluster, this task becomes highly coupled and nonlinear. A control methodology is proposed exploiting an orbit element difference description of the satellite relative motion.

11:30 AM AAS 04-260 Transient Stability of Motion Relative to a Stabilized Trajectory: Application to Formation Flight

F.Y. Hsiao and D.J. Scheeres, The University of Michigan

The transient stability of relative motion about a stabilized trajectory is investigated, with applications to the formation flight of spacecraft about a halo orbit. We first define the notion of transient stability and instability using the Krein Signature of the state transition matrix defining the relative motion. We provide examples of stable relative motion with and without transient stability, and characterize its effect on the robustness of a spacecraft formation control law. Using this approach we can prove the robustness of a class of formation flight control laws.

Wednesday, February 11, 8:30 AM Pikake

Session 20**:** Optimization and Control III

Chair: David Spencer
Pennsylvania State University

8:30 AM **AAS 04-261** **Fine-tuning of a Kalman Filter with a Genetic Algorithm and with Gradient-Based Optimization Methods**
Ousmane Gueye, Karina Lebel, and Jean de Lafontaine, Université de Sherbrooke

Kalman filters are well-known for their efficiency in reconstructing the best state estimates of a dynamical system from noisy measurements. This paper presents and compares three automated alternatives to the manual trial-and-error approach often used for the fine-tuning of the Kalman filter: the downhill simplex method, a genetic algorithm technique and, as a benchmark, a commercial numerical minimisation technique. A novel combination of these methods is proposed in the paper, resulting in an efficient tuning technique that optimizes the performance of the state estimator. The methods are evaluated by applying them on the estimation of a landing trajectory on Mars.

8:50 AM **AAS 04-262** **Maneuver Optimization for Fast Satellite Circumnavigation**
Stanley D. Straight and Steven G. Tragesser, Air Force Institute of Technology

The feasibility of satellite operations in close proximity to a chief satellite is of interest for both civilian and military applications. One such operation is circular circumnavigation in a time period less than the orbital period of the chief. This paper minimizes the required fuel consumption using discrete changes of velocity at specific burn points within a specified toroidal region centered on the circular-orbiting chief. An optimization scheme is demonstrated to produce the minimum number of burn points and their placements constrained by the deviation of the actual relative flight path from the nominal circular path.

9:10 AM **AAS 04-263** **On the Relation between the Local Formation Control Law and the Resulted Configuration**
Takanao Saiki, University of Tokyo; and Jun'ichiro Kawaguchi, The Institute of Space and Astronautical Science, Japan

In the formation flight missions, it is important to control the relative positions between the satellites. In case the formations consist of many satellites, the communication load becomes larger in the centralized system. One strategy that overcomes the flaws is to make each satellite be informed of the proximity relative information by others and control for itself. The paper discusses the new guidance law based on the regional limited information to control and maintain the formation. Especially, the relation between the local control laws and the resulted formation shape and the guidance stability of the formation are investigated.

9:30 AM **AAS 04-264** **Optimal Low-Thrust Orbital Transfers Around a Rotating Non-Spherical Body**
Gregory J. Whiffen, JPL

The NASA Discovery Program mission named DAWN will launch in 2006 to orbit the two giant asteroids Vesta and Ceres. The DAWN spacecraft will use solar-electric propulsion for both the interplanetary cruise and orbital operations at each asteroid. A method is required to design low-thrust orbital transfers between the science orbits given the complex gravity fields of the asteroids. This paper describes a technique for computing optimal low-thrust transfers for an arbitrarily complex, rotating gravity field. Optimal transfers involving point mass models and increasingly complex gravity fields are compared. The method is applied to a transfer between a high orbit and a low orbit with a plane change around the Asteroid Vesta using real mission constraints. Vesta's gravity is modeled with a harmonic expansion of order twenty. The Static/Dynamic Control algorithm is used to solve the optimal control problem.

9:50 AM AAS 04-265 Optimal Low-Thrust Trajectory Analysis for Constant and Variable Specific Impulse Thrusters Generated by Direct Methods and Multi-Objective Genetic Algorithms

Simone Rocca, Giannandrea Bianchini, Ernesto Benini, Stefano Casotto, Marco Manente, Giampaolo Navarro, and Daniele Pavarin, University of Padova

Constant and variable specific impulse electric propulsion are compared and their performances evaluated through the trajectory optimization of different missions. The main purpose of this paper is to evaluate whether the thrust modulation at constant power of a variable specific impulse engine may overcome the disadvantages deriving from its higher complexity and its likely lesser efficiency with respect to a constant specific impulse electric thruster. The optimization has been performed using both direct methods in optimal control and multi-objective genetic algorithms.

10:10 AM Break

10:30 AM AAS 04-266 Optimization In Sun-Synchronous Orbital Transfer

Jeng-Shing Chern, National Space Program Office (NSPO), Taiwan; and Yen-Hsun Chen, Far East Institute of Technology, Tainan

LATE WITHDRAWAL

The ROCSAT-2 is a small satellite of 750 kg mass designed for two remote sensing missions: earth observation and imaging of upward atmospheric lightning (red sprite). It shall be launched from Vandenberg on December 17, 2003. Both parking and mission orbits are sun-synchronous with altitudes at 723 and 891 km, respectively. For orbital transfer, Hohmann transfer technique shall be ... nclination before orbital ... nge. Since the circular ... n strategy one. Further ... ılation with continuous constant thrust. It might need more energy to complete the transfer. However, in case of the orbital transfer operation must be stopped due to any reason at any time, the resulted orbit is sun-synchronous. This advantage is worth a consideration.

10:50 AM AAS 04-267 Pareto Front and Sensitivity Analysis for Trajectory Optimization

Anthony L. Faulds, Trinnovations

The genetic algorithm using Pareto frontier and sensitivity analysis has many advantages over traditional optimization methods. This paper demonstrates how to apply sensitivity analysis in order to obtain a robust, optimal solution. Orbit trajectory and collision avoidance are two examples used to illustrate the strengths of this method. Utilizing the genetic algorithm with the Pareto frontier and sensitivity analysis allows the user to make a more informed decision about an optimal solution.

Session 21: Interplanetary Missions III

Chair: Louis D'Amario
Jet Propulsion Laboratory

1:30 PM AAS 04-268 Hopping Analysis on Regolith-like Surface of Small Planetary Bodies
Tetsuo Yoshimitsu, The Institute of Space and Astronautical Science, Japan

The author has proposed a hopping mobile system for roving vehicles over the micro-gravity environment of small planetary body surface. In our past study, the mobile system was analyzed and tested under the assumption that the rover moves over the rigid surface. But the asteroid surface may not be so rigid, because it is expected to be covered with soft soils (regolith). This paper is to find out the applicability of the proposed mobility to soft surface by the simulation analysis and micro-gravity experiments.

1:50 PM AAS 04-269 The Mars Reconnaissance Orbiter Mission Plan
Robert E. Lock, Peter Xaypraseuth, M. Daniel Johnston, C. Allen Halsell, Angela L. Bowes, Daniel T. Lyons, T. You, Dolan E. Highsmith, and Moriba Jah, JPL

This paper describes the Mars Reconnaissance Orbiter Mission Plan with emphasis on major mission activities and key challenges in mission design, spacecraft design, and science data acquisition. An overview of the mission will be provided which includes: the mission objectives, a description of the orbiter and its payloads, and the basic concept of operations. Also included will be a description of the science orbit at Mars and mission data return strategies.

2:10 PM AAS 04-270 Preliminary Results of Mars Exploration Rover In-Situ Radio Navigation
Joseph Guinn and Todd Ely, JPL

Preliminary results are presented from the first ever use of in-situ radio navigation measurements at Mars. NASA’s two Mars Exploration Rover (MER) spacecraft carry UHF-band radios for trajectory reconstructions of atmospheric descent and surface positioning phases. Reconstructions based on in-situ Doppler measurements between each MER and either the Mars Global Surveyor or Mars Odyssey orbiters are compared with traditional Direct-To-Earth Doppler and range measurements estimates. Accuracy improvements and reduced observations are realized by using in-situ radiometric measurements. In-situ measurement processing can be extended to future mission applications such as near real-time onboard trajectory determination and path planning.

2:30 PM AAS 04-271 Mars Exploration Rover Terminal Descent Mission Modeling and Simulation
Ben Raiszadeh and Eric M. Queen, NASA Langley Research Center

A detailed Entry, Descent, Landing (EDL) trajectory modeling and simulation has been developed to accurately predict the dynamics of the Mars Exploration Mission (MER) trajectory during the terminal descent phase of the EDL (parachute deployment, heatshield separation, deployment of the lander from the backshell, deployment of the airbags, descent rocket firings, etc.). This paper summarizes how the MER EDL sequence of events are modeled, verification of the methods used, and the inputs.

2:50 PM **AAS 04-272** **Systems for Pinpoint Landing at Mars**
Aron Wolf, JPL; Claude Graves, NASA Johnson Space Center; Richard Powell, NASA Langley Research Center; and Wyatt Johnson, JPL

Mars landers have been able to land only within tens to hundreds of km of a target site due to uncertainties in approach navigation, atmospheric modeling, and vehicle aerodynamics; as well as map-tie error and wind drift. The Mars Science Laboratory mission will improve this to 5 – 10 km using optical navigation and entry guidance. To achieve "pinpoint landing" (within 100m) for future missions, ways of addressing the remaining error sources (wind drift and map-tie error) must be found.

3:10 PM **Break**

3:30 PM **AAS 04-273** **Coordination of Mars Orbiting Assets to Support Entry, Descent, & Landing (EDL) Activities**
Joseph Neelon, JPL; Mark Wallace, University of Texas at Austin; and Lynn Craig, JPL

NASA policy requires continuous telecommunications with missions during the execution of their critical events, which implies constraints on where missions to other planets may land or inject into orbit. JPL is working to establish a telecommunications network at Mars to provide contact with inbound missions to Mars and assets that have landed on the Martian surface, thus reducing the constraints on where critical events may be performed. Coordination of network assets is required to cover an inbound mission's critical event, such as EDL. This paper describes the development of a tool to evaluate EDL coverage capability of Mars network assets over a specified launch date/arrival date space.

3:50 PM **AAS 04-274** **Autonomous Planetary Landing with Obstacle Avoidance: The Quartic Guidance Revisited**
Jean de Lafontaine, David Neveu, and Karina Lebel, Université de Sherbrooke

Future landing missions on distant planetary bodies will require some form of autonomous selection of the safest landing site. Past techniques have relied on so-called topographical cost maps to characterize each point of the reachable landing area in degrees of safety. This paper augments these topographical cost maps with fuel cost maps that express the effort (fuel, time) required in reaching the safest sites. An optimal time of flight to each potential target is computed using a quartic guidance law. Once the minimum-cost landing site is detected, this same guidance law generates the reference trajectory that guides the Lander to the safest site with minimum fuel.

4:10 PM **AAS 04-275** **Assessment of Per-Axis Thruster Control Authority of Cassini Spacecraft for Low-Altitude Titan Flybys**
Siamak (Sam) Sarani, JPL

Upon arrival at Saturn, Cassini will execute numerous low-altitude flybys of Titan and a few targeted icy satellite flybys. At the closest approach altitudes, the spacecraft must use its thrusters in order to overcome the external torques, maintain attitude control, and perform the required science slews. Because of the uncertainties associated with Titan atmospheric density model, as well as other uncertainties, the adequacy of thruster control authority at the closest approach must carefully be assessed to ensure that Cassini will not tumble out of control. The results indicate that even with conservative assumptions, there still exists adequate control authority margin.

4:30 PM AAS 04-276 Initial Operation Of Rocsat-2 --- The Second Satellite Of Roc
Jeng-Shing Chern, National Space Program Office (NSPO), Taiwan

LATE WITHDRAWAL

The ROCSAT-2 is a small satellite designed for two remote sensing missions: earth observation and imaging of upper atmospheric lightning (red sprite). An advanced remote sensing instrument of high performance, low mass, and simplicity in design is used for Earth observation. For the second ... ing. The integration and ... hed from Vandenberg on ... rking orbit with 723 km ... o to three revolutions to stabilize in attitude and to follow the magnetic field of Earth. Then the solar panels are deployed for battery charge. From the mission control center, a phase called early orbit mission operation is started. The satellite shall then be raised to the sun-synchronous mission orbit with altitude at 891 km. This paper shall present the actual flight results in different phases after separation.

4:50 PM AAS 04-277 Dynamics and Control of a Herd of Sondes Guided by a Blimp on Titan
Marco B. Quadrelli and Johnny Chang, JPL

This paper describes the model and the algorithm developed for the Titan aerobot blimp guiding and controlling a herd of sondes on the planet's surface. The paper summarizes the derivation of the equations of motion used in the simulation, and the details of the simulation model. A potential field controller is used for autonomous tracking of terrain features on the surface, and hazard avoidance. The result of simulation studies demonstrate that the method used for control is feasible even if significant uncertainty exists in the dynamics and environmental models, and provides the autonomy needed to enable surface science data collection.

Wednesday, February 11, 1:30 PM Pikake

Session 22**:** Special Session: Solar Sails II

Chair: Mike Lisano
Jet Propulsion Laboratory

1:30 PM AAS 04-278 The L1 Diamond Affair
Carl G. Sauer, Jr, JPL

The L1 Diamond is a configuration of four solar sail spacecraft traveling in roughly a diamond arrangement and situated on the Sun side of the Sun-Earth L1 LaGrange point. The science objectives for this mission are to observe and measure the spatial properties of the solar wind. The four solar sail spacecraft are separated from one another by 100 to 500 Earth radii depending upon the solar sail characteristic acceleration. Performance required by ideal sails, with perfect reflectance, and sails with more realistic physical properties are considered for various diamond configurations.

1:50 PM AAS 04-279 Optimal Counter-Intuitive Solar Sail Escape Trajectories
John W. Hartmann, Victoria L. Coverstone, and John E. Prussing, University of Illinois at Urbana-Champaign

The problem of escape from gravity fields of celestial bodies small relative to Earth is addressed. Results of optimizations using a direct transcription optimization algorithm utilizing collocation are presented. These results indicate that previous assumptions of the near-optimality of maximizing instantaneous rate of increase of total orbit energy to attain minimum time escape may not always be correct. Under some circumstances, reduced escape times can be achieved by temporarily decreasing orbital energy at opportune points along the escape trajectory. These unanticipated results have motivated the development of a feasible trajectory generator using a search technique known as a rapidly-exploring random tree that is capable of negotiating multi-modal search spaces to find counter-intuitive escape trajectories i.e. trajectories that move inward towards the central body before escaping. These feasible trajectories can then be used as initial guesses for gradient based optimization techniques.

2:10 PM AAS 04-280 Earth Escape Using a Slowly-Rotating, Doubly-Reflective Solar Sail
Michael A. Swartwout, Washington University

Recent work has demonstrated Earth escape from a geosynchronous transfer orbit using a solar sail. However, such methods require significant slew rates and thus large, heavy attitude control components. It is desirable to develop an escape method compatible with low-authority actuators such as tip vanes. This paper investigates Earth escape using a slowly-rotating solar sail that is reflective on both sides; this approach significantly reduces control torques while achieving comparable escape times. The optimal sail orientation is derived, the behavior of the rotating sail is evaluated for control authority and consistency, and escape performance is compared to an existing method.

2:30 PM AAS 04-281 A Comparison of Solar Sail Control Methods in Geosynchronous Transfer Orbits
Jeremy S. Neubauer and Michael A. Swartwout,Washington University

Several important applications for solar sails involve operating in planetary orbits, requiring significantly greater control authority than in solar orbits. Most research in sail trajectories assumes that rotational and translational dynamics can be decoupled— that is, the sail can perfectly track the commanded orientation. This assumption is tested for three sail control methods under the demanding rotational requirements of Earth escape. Simulation indicates that both center-of-mass (CM) and center-of-pressure (CP) control are sufficient; however, both are difficult to implement. A hybrid CM/CP control method is devised and demonstrated a successful and implementable method of decoupling rotational and translational dynamics.

2:50 PM **AAS 04-282** **Solar Sail Attitude Control Sensitivity to Solar Radiation Pressure Model Accuracy**
Jeff Bladt, Ball Aerospace Corp.; and Dale Lawrence, University of Colorado

Sensitivity of solar sail attitude control performance to accuracy of the solar radiation pressure (SRP) model is characterized. Solar sail configurations using articulated vanes located at the sail periphery to produce attitude control torque employ assumed SRP models to generate vane deflection angle commands. Attitude control performance sensitivity is presented for various methodologies, including a Jacobian pseudo-inverse and feedback inversion, used to map desired control torque into commanded deflection angles. Simulation results quantify the effects of SRP model errors on sailcraft attitude control performance.

3:10 PM **Break**

3:30 PM **AAS 04-283** **A Solar Sail Integrated Simulation Toolkit**
Jordan Ellis, Michael Lisano, Peter Wolff, and James Evans, JPL; Jeff Bladt, Ball Aerospace; Dan Scheeres and Leonel Rios-Reyes, University of Michigan; and Dale Lawrence, University of Colorado

This paper describes an integrated set of high fidelity software tools that are being developed for the design of solar sail missions and analysis of the guidance, navigation and control (GNC) of these missions. This integrated set of simulation tools will be able to predict, re-calibrate and optimize the trajectory, maneuvers and propulsive performance of a sail during a representative flight mission. This tool has capabilities for mission design and for simulation of the sail attitude determination and control, navigation based on ground based and on board tracking, feedback control performance evaluation, parameter estimation and covariance analysis and analysis of attitude control systems. It is capable of evaluating the sail performance accounting for structural dynamic effects, billowing, bending and material degradation effects. The paper will also describe the use of a prototype delivery of the toolkit to analyze the GEOSTORM mission-which is designed to place and maintain an observing spacecraft at a Sun-Earth libration point (sub-L1) at a distance of 3.0 million kilometers from the Earth.

3:50 PM **AAS 04-284** **A "Yank and Yaw" Control System for Solar Sails**
David "Leo" Lichodziejewski, Billy Derbes, and Gordon Veal, L'Garde, Inc.

L'Garde sail designs use vanes for stability and control. A control scheme is presented which takes advantage of passive stabilization, in an aircraft-like arrangement. All four vanes are Canted anti-sunward for passive stabilization in pitch and roll. Roll angle remains constant. The Cant angles of the fore and aft vanes are retrimmed to come to a new stable pitch attitude, similar to retrimming aircraft elevators. The port and starboard vanes are differentially "Twirled" about the beam axis to yaw the vehicle, similar to the rudder function of aircraft. A maneuver is pitch-then-yaw, similar to an aircraft "Yank and Bank."

4:10 PM **AAS 04-285** **Robust Thrust Control Authority for a Scalable Sailcraft**
David Murphy, ABLE Engineering Co. Inc.; and Bong Wie, Arizona State University

Detailed trades and analyses necessary for, and resulting in, the selection of a robust method of attitude control for a scalable 3-axis stabilized sailcraft are described. Comparison of actuator options, in combination with a mechanical architecture for a scalable square solar sail, determines the best fit with near-term sail mission control needs.

4:30 PM AAS 04-286 Navigation Models of Solar Sails: Modeling a Circular Sail with Billow

Leonel Rios-Reyes and Daniel J. Scheeres, The University of Michigan

To successfully navigate a solar sail spacecraft requires that a precision propulsion model be defined. Such a model must incorporate all the relevant deviations of a sail from its ideal shape in a tractable form that will allow the model to be refined in-flight based on tracking data. As a first step in this direction we study the effect of billow on a non-ideal circular solar sail. Using an analytical representation of the billow, approximate solutions for the force, moments, and center of pressure are found. Using these results we study the effect of billow on the total thrust and trajectory of the sail and ascertain the observability of these deviations.

Wednesday, February 11, 1:30 PM Plumeria

Session 23: Orbital Mechanics IV

Chair: Bob Melton
Pennsylvania State University

1:30 PM **AAS 04-287** **Representations of Invariant Manifolds for Applications in Three-Body Systems**
K. Howell, Purdue University; M. Beckman, NASA Goddard Space Flight Center; C. Patterson, Purdue University; and D. Folta, NASA Goddard Space Flight Center

The Lunar L1 and L2 libration points have been proposed as gateways granting inexpensive access to interplanetary space. To date, only individual solutions to the transfer between three-body systems have been found. The methodology to solve the problem for arbitrary three-body systems and entire families of orbits does not exist. This paper presents the initial approaches to solve the general problem for single and multiple impulse transfers. Two different methods of representing and storing 7-dimensional invariant manifold data are presented. Some particular solutions are presented for two transfer problems, though the emphasis is on developing methodology for solving the general problem.

1:50 PM **AAS 04-288** **The Role of Invariant Manifolds in Low Thrust Trajectory Design**
Martin W. Lo, JPL; Rodney Anderson, University of Colorado; and Gregory Whiffen and Larry Romans, JPL

We explore the role of invariant manifolds in the design of low thrust trajectories. We review basic concepts for temporary capture and escape used to describe the Petit Grand Tour concept for an impulsive tour of the Icy Moons. We then examine a portion of a representative trajectory for the Jupiter Icy Moons Orbiter mission (JIMO) designed with the MYSTIC optimization tool and study its interaction with the invariant manifolds of unstable resonant orbits as well as libration orbits.

2:10 PM **AAS 04-289** **Application of Dynamical Systems Theory to a Very Low Energy Transfer**
Shane Ross and Wang Sang Koon, California Institute of Technology; Martin W. Lo, JPL; and Jerrold E. Marsden, California Institute of Technology

We use lobe dynamics in the restricted three-body problem to design orbits with prescribed itineraries with respect to the resonance regions within a Hill's region. The application we envision is the design of a low energy trajectory to orbit three of Jupiter's moons using the patched three-body approximation (P3BA). We introduce the "switching region," the P3BA analogue to the "sphere of influence." Numerical results are given for the problem of finding the fastest trajectory from an initial region of phase space (escape orbits from moon A) to a target region (orbits captured by moon B) using small controls.

2:30 PM **AAS 04-290** **Coupled Effects of Initial Orbit Plane on Orbit Lifetime in the Three Body Problem**
Christopher J. Scott and David B. Spencer, The Pennsylvania State University

In this paper, the orbital dynamics of spacecraft orbiting the smaller gravitational mass with a larger gravitational body perturbing its orbit is addressed. While the simple two-body dynamics works well for relatively isolated systems, objects orbiting a body with such a large gravitational perturbation require modeling the system as a restricted three-body problem. An example of this type of system is Jupiter and one of its moons. This study examines the stability of orbits at various inclinations and right ascensions with regards to orbital lifetimes, and answers the question of how long does it take before the gravitational forces of the larger body causes the spacecraft to crash into the smaller body. This information is critical when planning a mission to a moon, especially when one of the goals is to orbit the moon at as low of an altitude as possible. An example analysis for a spacecraft orbit around Ganymede is presented.

2:50 PM **AAS 04-291** **The Dynamics of Orbits in A Potential Field of a Solid Circular Ring**
Roger A. Broucke, University of Texas at Austin; and Antonio Elipe, University of Zaragoza

We study the properties and perturbations of orbits around a central planet surrounded by a ring. The potential and accelerations can be evaluated in terms of complete elliptic integrals of the first and second kind. We first looked at planar periodic orbits (and their stability), both in the plane of the ring and orthogonal to it. Next, we have studied the orbits around a central body with a massive circular ring. We mainly want to evaluate the perturbation of the Asteroid belt on the osculating orbit elements of a nearby planet such as Mars, assuming that the mass of the belt is about one Earth mass. Finally we compare the continuous solid ring model with Maxwell's ring composed of discrete masses in circular orbit.

3:10 PM **Break**

3:30 PM **AAS 04-292** **Orbits Around an Elongated 3D-Object Such as the Asteroid Eros**
Roger A. Broucke, University of Texas at Austin; and Antonio Bertachini Prado, Sao Jose dos Campos, SP.Brazil

We study the properties of orbits around an elongated rectangular object, in an attempt to model the motion near an Asteroid such as Eros. We do this with some truly 3-dimensional homogeneous mass distributions. We use a rather simple formulation, first given by Bannerjee and Das Gupta in 1977, consisting purely of Arc-Tangents and Logarithms. We studied both two and three-dimensional orbits around a fixed or uniformly rotating rectangular body. We mainly want to evaluate the perturbation of the elongated shape on the osculating orbit elements of a nearby satellite or spacecraft. Finally we compare the model with B. Werner's Polyhedron formulation for arbitrary shapes.

3:50 PM **AAS 04-293** **Lambert's Theorem – A Complete Series Solution**
James D. Thorne, Air Force Office of Scientific Research

Lambert's theorem states that the orbital transfer time between two known positions in the 2-body problem is dependent only on the semi-major axis, given two fixed position vectors and a known gravitational constant. The associated Lagrange equations for the orbital transfer time may be expressed as series expansions for all cases. Because of the case dependence, several different solution approaches are necessary among the three distinct forms of the series equations. Two new solutions are given for each boundary of long-way orbital case and are also compared with an earlier result for short-way transfers. Convergence properties of the new series solutions are investigated numerically for a variety of example orbits.

4:10 PM **AAS 04-294** **Relative Spacecraft Motion: A Hamiltonian Approach to Eccentricity Perturbations**
Egemen Kolemen and N. Jeremy Kasdin, Princeton University

This paper uses a Hamiltonian approach to find the effects of eccentricity perturbations on the linearized relative motion of spacecrafts described by Hill's equations. Perturbations to the constant canonical elements, obtained by a Hamiltonian treatment of the linearized relative motion, will be considered. To begin with, the relative motion is described in an eccentric reference frame. Subsequently, the perturbing Hamiltonian is found in terms of eccentricity. Next, a perturbation analysis is carried out via a variation of parameters procedure, generating a closed-form solution for the eccentric reference orbit. Finally, using the orbit-averaged equations, the eccentricity effects on boundedness are discussed.

4:30 PM **AAS 04-295** **Satellite Constellation Design for Mid-Course Ballistic Missile Intercept**

Luke M. Sauter, Ronald J. Proulx, and Howard Musoff, Draper Laboratory

This paper will establish a conceptual approach to the design of satellite-based mid-course missile defense. This intercept problem leads to a new paradigm of coverage for constellation design where interceptor "reachability" replaces visual coverage. Previous constellation designs, based on ground coverage by symmetrical patterns of circular orbits, provide an initial basis for design. Abstracted Walker's Star and Delta patterns, as well as area-specific constellation designs provide bounds on the number of satellites required. From these design methods, both genetic algorithms and gradient based optimization schemes are used to explore and refine the constellation design space.

Session 24: Formation Flying III

Chair: Jay Middour
Naval Research Laboratory

1:30 PM **AAS 04-296** **Close Spacecraft Formation Keeping**
Pierre Vignal and Henry Pernicka, University of Missouri-Rolla

The University of Missouri–Rolla recently initiated a project to design and build a pair of tethered satellites. This project is designated as the MR SAT Project (Missouri–Rolla Satellite), and is composed of two spacecraft linked to each other with a ten meter long tether. The two main mission objectives are to experiment with the use of tethers to fly satellites in formation and to establish a wireless communication network between the two satellites based on low-cost technologies. The final phase of the mission will consist of releasing the tether and then attempting to maintain the ten meter separation by using onboard propulsion systems. This document describes a comparison of different possible designs of the active control system.

1:50 PM **AAS 04-297** **Constellation Design with Uniformly Distributed Satellites**
Keunjoo Park and Daniele Mortari, Texas A&M University

In this paper we propose a methodology to build constellations made with satellites uniformly distributed in the celestial sphere using the recently proposed Flower Constellations (FCs). The main advantage of using FCs is that they allow to design symmetrical dynamics with a judicious/proper distribution of the satellites in the admissible slots. Moreover, in an Earth-Centered Earth-Fixed (ECEF) system of coordinates, all the satellites of a given FC follow the same repeating ground track, a very useful property.

2:10 PM **AAS 04-298** **Geometric Approach to Orbital Formation Mission Design**
Matthew J. Press and Steven G. Tragesser, Air Force Institute of Technology

For a distributed sensing architecture to be useful for collecting scientific data, it is essential to have a methodology for relating the orbital formation parameters to the remote sensing requirements. An algorithm is created to attain a given spatial distribution of multiple satellites viewed from a target ground site as a function of the target site latitude, target site longitude, the formation orientation geometries and the formation's circular orbit reference plane. This tool will enable mission planning for orbital formation reconfiguration as well as future concept exploration.

2:30 PM **AAS 04-299** **Flower Constellations for Global Navigation Applications**
Marco Maria Castronuovo and Francesco Longo, University of Rome "La Sapienza

LATE WITHDRAWAL

Recently a new interest has grown around the possible use of satellite constellations that generalize the multi-stationary orbits, having repeating ground tracks. They have been named the Flower Constellations (Mortari et al., 2003). In this paper the possible use of the Flower Constellations for [illegible] is very well suited for [illegible] orbits. However, it is [illegible] several configurations have [illegible] ments and the optimum number of petals and satellites. A significantly lower number of satellites than that of the standard GPS system is shown to be required by a Flower Constellation-based Global Positioning System.

2:50 PM **AAS 04-300** **Hovercraft Satellite Simulation Test-Bed**
Benjamin Essenberg, Joseph A. Sarokhan, and N. Jeremy Kasdin, Princeton University

Numerous future NASA missions call for formations of satellites to perform the functions previously accomplished by single, large spacecraft. In particular, as the need for larger aperture telescopes grows, the space science community is turning to interferometer systems to achieve the advances in resolution and collecting area. Building these systems, which require exquisite precision in relative positioning, will required advances in modeling, simulation, and test as well as control system design. At Princeton, we are building a fleet of hovercraft vehicles that will simulate the optical bench of an interferometer element in space. These vehicles will eventually have full 6 degree-of-freedom control. By operating them in the ice rink we are able to perform very large area experiments. This paper describes the manufacture and test of our first prototype vehicle, including closed loop positioning control, and presents the design of our next generation testbed.

3:10 PM **Break**

3:30 PM **AAS 04-301** **Low-Thrust Formation Flight For Astronomy Satellite**
Hiroshi Yamakawa, Institute of Space and Astronautical Science

Formation flight using low-thrust propulsion is analytically investigated motivated by the X-ray astronomy satellite XEUS mission. XEUS is an Earth orbiting formation flight mission, which consists of a mirror satellite and a detector satellite, whose relative distance is kept 50m corresponding to the focal distance of the telescope. This requires consecutive relative position keeping in inertial frame for observation purpose via low thrust engine. This paper discusses the strategy for relative position keeping with low thrust operation, by adopting Hill's equation, which describes the relative motion of the detector satellite around the mirror satellite in a circular orbit. Furthermore, preliminary satellite design is performed assuming the altitude of the circular orbit and the relative distance between two satellites as the design parameters.

3:50 PM **AAS 04-302** **Mihail Satellite Constellation**
Michael Furman, Harris Government Communications Systems Division

NASA communications are used to acquire mission data from low earth orbit (LEO) satellites. Twenty missions use the geostationary Space Network (SN) and 30 use the Ground Network (GN). The Mihail Satellite Constellation (MSC) is competitive with the SN/GN to support a broad range of LEO missions with diverse orbit parameters. Three communication metrics for versatility are defined as optimization criteria; constellation-to-ground terminal availability, range between mission-to-constellation, and constellation design life. Preliminary results suggest that a 2-ground terminal/12-ball MAC provides comparable SN/GN availability, longer contact times, while radio power margins can be reduced by 15 dB.

4:10 PM **AAS 04-303** **The Design and Development of the GRACE Mission Analysis Tool**
Jeffery Mauldin, Srinivas Bettadpur, and Wallace Fowler, The University of Texas at Austin

The Gravity Recovery and Climate Experiment (GRACE) mission provides a unique opportunity for the development of a mission analysis tool capable of analyzing the current status of the twin satellite system and predicting future performance characteristics of the satellites' onboard instrumentation. The mission analysis tool provides services for GRACE mission operations and science teams, as well as an outlet for education advancements. Data visualizations, instrument fault isolation, science data quality verification, tracking of trends in instrument behavior over the lifetime of the mission, and prediction of future instrumentation performance provide mission operations and science teams with useful information for analysis tasks. Educational benefits arise from the opportunity for students to learn from real examples, comparing the data characteristics of the GRACE mission to classroom exercises.

4:30 PM **AAS 04-304** **Formation Flying and Constellation Station Keeping in Near-Circular Orbits**
Xiaodong Duan and Peter M. Bainum, Howard University

If the spacecraft in near-circular orbits (including circular orbit) satisfy the given constraints, the relative secular drifts due to the non-spherical Earth's perturbation would vanish between the orbits. Therefore the designed orbits can be used for formation flying and constellation station keeping. The solution is one of the solution sets drawn from a general solution in the sense of a first-order approximation. The method is compared with the zero solution for the same problems and the significance of the method is explained. Results from high precision simulations show the accuracy and effectiveness of the method. The influence of drag on this approach is also demonstrated through the simulation.

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