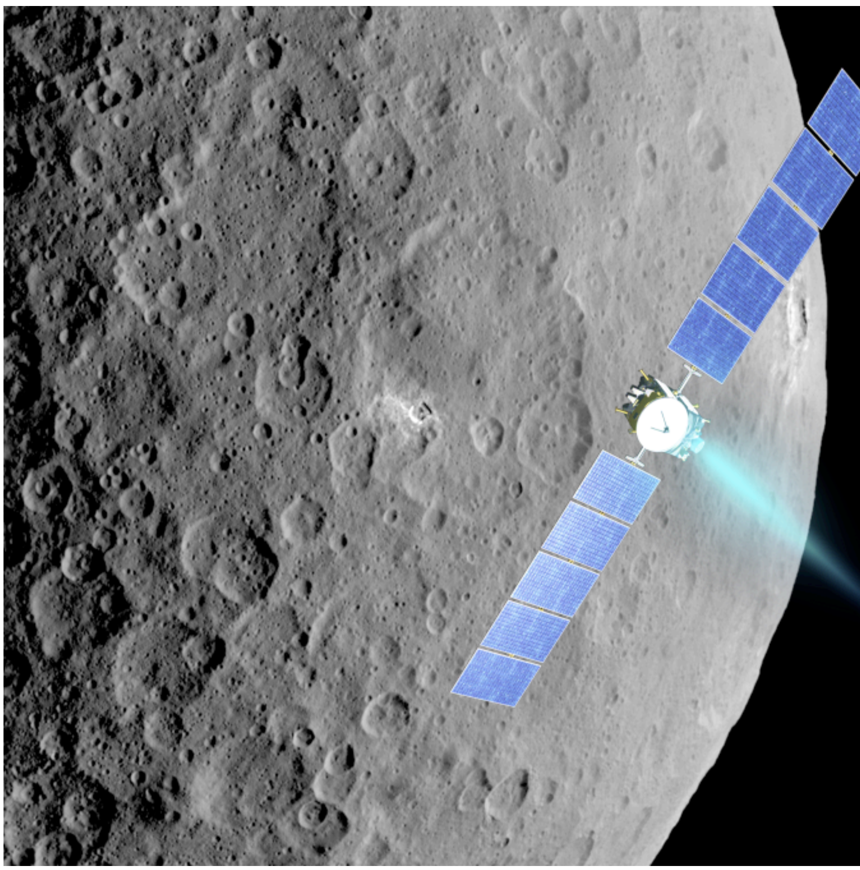
27th AAS/AIAA Space Flight Mechanics Meeting

February 5-9, 2017

San Antonio, Texas



AAS General Chair
Dr. Frederick Leve
Air Force

AIAA General Chair
Dr. Jon Sims
Jet Propulsion Laboratory

AAS Technical Chair
Dr. Jay McMahon
University of Colorado

AIAA Technical Chair
Dr. Yanping Guo
Johns Hopkins University
Applied Physics Lab

27TH AAS/AIAA SPACE FLIGHT MECHANICS MEETING

GENERAL INFORMATION

Welcome to the 27th Space Flight Mechanics Meeting, hosted by the American Astronautical Society (AAS) and co-hosted by the American Institute of Aeronautics and Astronautics (AIAA), February 5 – 9, 2017. This meeting is organized by the AAS Space Flight Mechanics Committee and the AIAA Astrodynamics Technical Committee, and held at the Marriott Plaza San Antonio, 555 South Alamo Street, San Antonio, TX 78205, (210)-229-1000, http://www.marriott.com/hotels/travel/satpl-marriott-plaza-san-antonio/.

REGISTRATION

Registration Site (https://www.xcdsystem.com/aas/index.cfm)

In order to encourage early registration, we have implemented the following conference registration rate structure: **Register by December 23, 2016 and save $70!**

Category	Early Registration (through Dec 23, 2016)	Registration	Walk-up Registration (after Jan 20, 2017)
Full - AAS or AIAA Member	$550	$620	$720
Full - Non-member	$650	$720	$820
Retired or Student* - Member	$200	$270	$370
Retired or Student* - Non-member	$250	$320	$420

**does not include proceedings CD*

A 10% fee will be assessed for all refunds. No refunds will be issued after 8:00 am CST February 6, 2017.

One ticket to the Jack Guenther Pavilion at the Brisco Western Art Museum for dinner on Tuesday evening is included with every registration. Please be sure to bring a valid photo ID in order to be served. Guest tickets for the dinner may be purchased for $75. More information about the dinner is included below.

All registrants and guests are invited to the welcome reception on Sunday evening for food and drinks.

A conference registration and check-in table will be located in the La Villita Foyer of the Marriott Plaza Hotel and will be staffed according to the following schedule:

- Sunday February 5: 3pm – 6pm
- Monday February 6: 7:30am – 12pm
- Tuesday February 7: 8am – 12pm
- Wednesday February 8: 8am – 12pm
- Thursday February 9: 8am – 10 am

We will accept registration and payment on-site for those who have not pre-registered online, but we strongly recommend online registration before the conference in order to avoid delays (see URL above). Pre-registration also gives you free access to pre-print technical papers. On-site payment by credit card will be only through the AAS website using a computer at the registration table. Any checks should be made payable to the "**American Astronautical Society.**"

SCHEDULE OF EVENTS

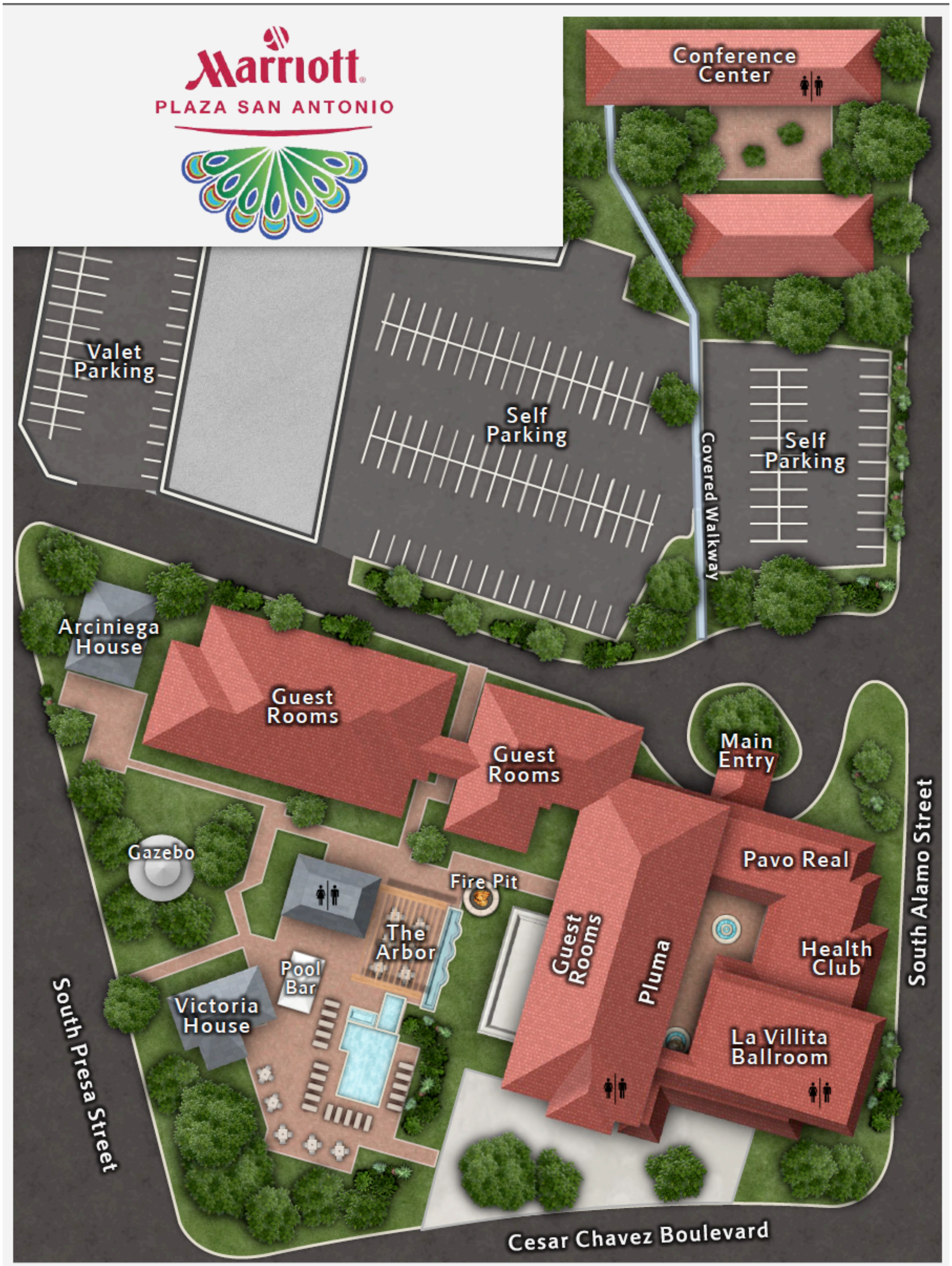
Technical sessions begin on Monday, February 6, at 8 am. The last technical sessions end at 1:00 pm on Thursday, February 9. Presentations are limited to 15 minutes with an additional 5 minutes for questions and answers. Each session has a 20-minute morning or afternoon break. Authors are required to be in their session room 30 minutes prior to the start of their sessions. No speakers' breakfast will be served.

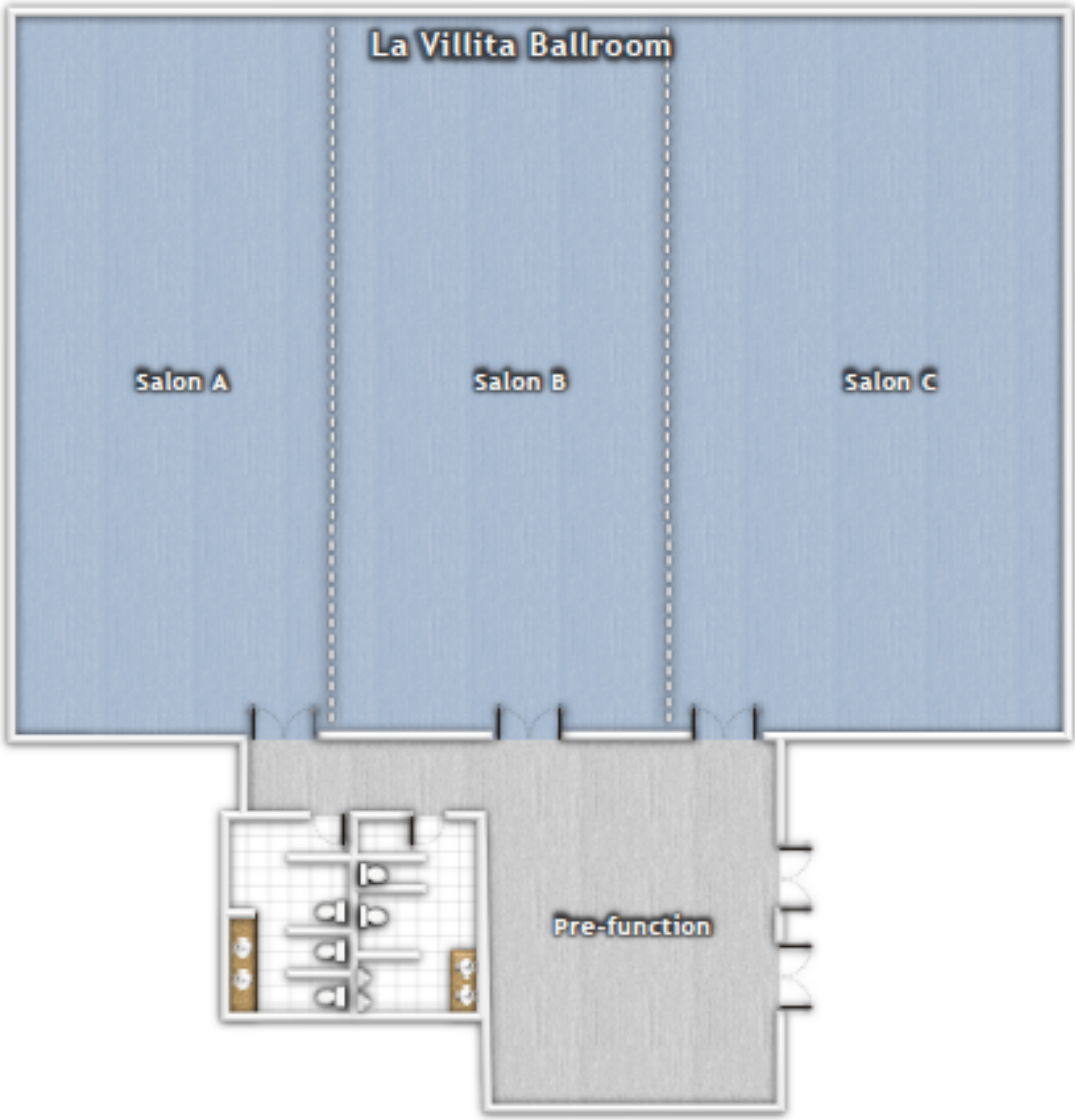
Day	Start	End	Function	Room
Sunday 5 February	3pm	6pm	Registration	La Villita Foyer
	6pm	9pm	Early Bird Reception (Food and Bar)	La Villita C
Monday 6 February	7:30am	12pm	Registration	La Villita Foyer
	8am	12pm	Session 1: Asteroid Missions 1	La Villita A
	8am	12pm	Session 2: Trajectory Optimization 1	La Villita B
	8am	12pm	Session 3: Rendezvous and Proximity Operations 1	La Villita C
	8am	12pm	Session 4: Space Situational Awareness 1	Pavo Real
	10am	10:20am	Morning Break	
	Noon	1:30pm	Joint Technical Committee Lunch	Cavalier
	1:30pm	4:50pm	Session 5: Launch and Landing Operations	La Villita A
	1:30pm	4:50pm	Session 6: Trajectory Design	La Villita B
	1:30pm	4:50pm	Session 7: Dynamical Systems Theory Applied to Space Flight	La Villita C
	1:30pm	4:50pm	Session 8: Satellite Constellations	Pavo Real
	3:30pm	3:50pm	Afternoon Break	
	5pm	6pm	Dirk Brouwer Award Plenary and Breakwell Student Travel Award Presentation	La Villita

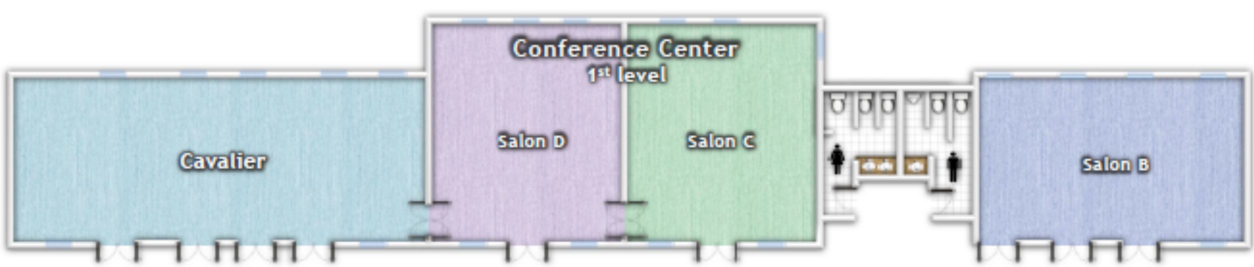
Day	Start	End	Function	Room
Tuesday 7 February	8am	12pm	Registration	La Villita Foyer
	8am	12pm	Session 9: Planetary Missions	La Villita A
	8am	12pm	Session 10: Trajectory Optimization 2	La Villita B
	8am	10am	Session 11: Space Situational Awareness 2	La Villita C
	8am	12pm	Session 12: Dynamics and Control of Large Space Structures and Tethers	Pavo Real
	10am	10:20am	Morning Break	
	10:20am	12pm	Session 25: Special Session: Interdisciplinary Challenges in Space Situational Awareness	La Villita C
	Noon	1:30pm	AIAA Technical Committee Lunch	Cavalier
	1:30pm	6:10pm	Session 13: Asteroid Missions 2	La Villita A
	1:30pm	6:10pm	Session 14: Orbital Dynamics 1	La Villita B
	1:30pm	6:10pm	Session 15: Orbit Determination and Space-Surveillance Tracking	La Villita C
	1:30pm	6:10pm	Session 16: Attitude Dynamics and Control 1	Pavo Real
	3:30pm	3:50pm	Afternoon Break	
	6pm	10pm	Offsite Event: Dinner at the Brisco Western Art Museum	Jack Guenther Pavilion
Wednesday 8 February	8am	12pm	Registration	La Villita Foyer
	8am	12pm	Session 17: Earth and Lunar Missions	La Villita A
	8am	12pm	Session 18: Navigation	La Villita B
	8am	12pm	Session 19: Rendezvous and Proximity Operations 2	La Villita C
	8am	12pm	Session 20: Attitude Dynamics and Control 2	Pavo Real
	10am	10:20am	Morning Break	
	Noon	1:30pm	AAS Technical Committee Lunch	Cavalier

Day	Start	End	Function	Room
Wednesday 8 February	1:30pm	5:10pm	Session 21: Asteroid Missions 3	La Villita A
	1:30pm	6:10pm	Session 22: Orbital Debris	La Villita B
	1:30pm	6:10pm	Session 23: Formation Flying and Relative Motion	La Villita C
	1:30pm	6:10pm	Session 24: Guidance and Control	Pavo Real
	3:30pm	3:50pm	Afternoon Break	
	7:00pm	8:00pm	Conference Administration Subcommittee	La Villita A
	7:00pm	8:00pm	Technical Administration Subcommittee	La Villita B
	7:00pm	8:00pm	Website Administration Subcommittee	La Villita C
Thursday 9 February	8am	10am	Registration	La Villita Foyer
	8am	12pm	Session 26: Trajectory Design and Optimization	La Villita A
	8am	12:20pm	Session 27: Orbital Dynamics 2	La Villita B
	8am	11:40am	Session 28: Orbit and Attitude Determination	La Villita C
	8am	12pm	Session 29: Attitude Dynamics and Control 3	Pavo Real
	10am	10:20am	Morning Break	

Maps of the Marriott Plaza Hotel and the relevant meeting rooms appear on the following pages.


Marriott
PLAZA SAN ANTONIO
Conference Center
Valet Parking
Self Parking
Covered Walkway
Self Parking
Arciniega House
Guest Rooms
Guest Rooms
Main Entry
Pavo Real
Gazebo
Fire Pit
The Arbor
Guest Rooms
Pluma
Health Club
Pool Bar
Victoria House
La Villita Ballroom
South Presa Street
South Alamo Street
Cesar Chavez Boulevard


La Villita Ballroom
Salon A
Salon B
Salon C
Pre-function


Conference Center
1st level
Cavalier
Salon D
Salon C
Salon B

Special Events

Early Bird Reception

Sunday, February 5 6:00 – 9:00 pm

Location: La Villita C

Menu

Grilled Vegetables & Mozzarella on Rosemary Skewer

Seared Asparagus and Prosciutto Wraps

Top Round Beef

Turkey

Vegetable Spring Rolls

Dirk Brouwer Award Plenary and Breakwell Travel Award Presentation

Monday, February 6 5:00 – 6:00 pm (Ceremony and Lecture)

Location: La Villita (Ceremony and Lecture)

There will also be presentations for the best paper award from the 2016 Space Flight Mechanics conference and for an AAS Fellow.

Analytic Exploration in Astrodynamics

There are very few problems in astrodynamics that yield to an exact analytical solution. However, hope should not be lost. It is possible to gain analytical insight into the general behavior of the solution. A well-known example is the effect of Earth oblateness on the movement of the orbit right ascension and the stability of argument of perigee at the critical inclination. This talk will take a look at a variety of problems and techniques for achieving some level of analytical insight into their behavior. We will find that sometimes it is useful to find a problem you can solve that is sufficiently close to the problem that you can't solve. Even if the problem must be solved numerically, analytical insights may provide improved efficiency in guiding the numerical investigation.

DIRK BROUWER AWARD HONOREE

Felix R. Hoots is an Aerospace Fellow in the Systems Analysis and Simulation Subdivision of The Aerospace Corporation and is based in Colorado Springs, Colorado. He is responsible for providing direct support to a variety of DoD and other agency customers as well as providing integration and cross-customer synergy advice to Aerospace management.

With over 40 years of experience in space surveillance, Hoots is widely recognized for his contributions to both the theoretical as well as the operational side of the Space Surveillance Network and association processing centers.

Prior to joining Aerospace, he worked as an astrodynamicist for the 14th AF and NORAD/ADCOM (later Air Force Space Command) and then as a Chief Scientist for GRC International (later AT&T Government Solutions). As a civil servant he was instrumental in developing satellite orbital prediction models and close approach algorithms used to maintain the catalog of satellites. A particular highlight was his work performed jointly with the Navy to develop algorithms to remove incompatibility between data products from Air Force Space Command and those from Naval Space Command. His work as a contractor supported the Air Force and Navy as well as other agency customers in their space and surveillance activities. During this time he worked with the Naval Research Lab to do the first proof of concept demonstration of an all Special Perturbations satellite catalog.

His stature in the community has been recognized with 24 publications in international professional journals including two commissioned encyclopedia articles and eight proceedings. He has been an invited speaker at NATO and International Astronomical Union (IAU) conferences and was technical organizer and speaker at a series of US/Russian Space Surveillance Workshops beginning in 1994 and continuing to the present.

Hoots earned a bachelor's degree in physics and a master's degree in mathematics from Tennessee Technological University. He earned a PhD in mathematics with an emphasis in astrodynamics from Auburn University.

Hoots is a Fellow of the American Astronautical Society and an Associate Fellow of the American Institute of Aeronautics and Astronautics. He has previously served on the board of directors of the American Astronautical Society and as an Associate Editor of the AIAA Journal of Guidance, Control, and Dynamics.

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DINNER AT THE BRISCO WESTERN ART MUSEUM

Tuesday, February 7	6:00 – 8:00 pm (Hosted Call Bar)
	7:30 – 9:00 pm (Dinner)
	8:00 – 10:00 pm (Cash Bar)
Location	Jack Guenther Pavilion at the Brisco Western Art Museum

The Briscoe Western Art Museum, named in honor of the late Texas Governor, Dolph Briscoe, Jr. and his wife, Janey, preserves and interprets the art, history, and culture of the American West through engaging exhibitions, educational programs, and public events reflective of the region's rich traditions and shared heritage.

Located on San Antonio's famed River Walk, the institution is housed in San Antonio's first Public Library and newly constructed pavilion designed by the nationally recognized architecture firm Lake|Flato. The Briscoe Campus consists of the historic Museum building, the Jack Guenther Pavilion and the adjacent McNutt Sculpture Garden spread across one-and-a-quarter acres in downtown San Antonio.

The Briscoe Western Art Museum presents art and artifacts from across the history and cultures of the American West. Over five centuries, from the Spanish conquest to the present day, the collections of the Briscoe tell the story of the West in all its drama. It is a story of global dimension, played out in a timeless landscape. It is a story that continues today. What does the West mean to you? What future are we pioneering for the generations who will follow us?

The Briscoe Western Art Museum is located in downtown San Antonio along the River Walk at 210 West Market Street. It is less than half mile walk from the Marriott Plaza San Antonio.

The museum will be open with free admission until 9 pm on the day of our event.

Conference registration fees include admission for one person to the dinner. Guest tickets are available for $75 each on the conference registration site.

A map from the conference hotel to the Briscoe Western Art Museum is on the next page.


W Market St
The Davenport Lounge
N Presa St
Whataburger
Casa Rio
Losoya St
S Alamo St
Sign in
Riverwalk, San Antonio
Hotel Contessa
Briscoe Western Art Museum
River Walk
E Market St
E Market St
San Antonio River Walk
CPS Energy
S Presa St
Hilton Palacio Del Rio
Drinking Fountain
Consulate
Villita St
River Art Group
CPS Energy Parking
River Walk
Gallery
Arneson River Theatre
Fig Tree
Villita St
Villita St
8 min
0.4 mile
Exhibition H
Box Office
S St Mary's St
O'Brien Historic Riverwalk, an Ascend...
Guadalajara Grill
Galleria II
La Villita Historic Arts Village
Rio De Gelato
Drinking Fountain
E Nueva St
Nueva Street Gallery
E Nueva St
8 min
0.4 mile
Hemisfair Park
The Fairmount
SpringHill Suites San Antonio Downtown/...
Magik Children's Theatre
Arciniega St
Arciniega St
Arciniega St
Yanaguana Garden and playground
Tolle Pl
Marriott Plaza San Antonio
Anaqua Grill
San Antonio BCycle
Calavera's Tattoo
Satellite
E César E. Chávez Blvd
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Google
Map data ©2017 Google
Terms
Send feedback
100 ft

Conference Location

Marriott Plaza San Antonio

555 South Alamo Street
San Antonio, Texas 78205
marriott.com/hotels/travel/satpl-marriott-plaza-san-antonio/
(210) 229-1000

You'll remember much more than The Alamo when enjoying the well-appointed amenities at Marriott Plaza San Antonio. Sitting on 6 acres of natural, lush Texas landscape, the hotel boasts plenty of shade from cypress and palm trees for a casual stroll. Dine at Anaqua Restaurant & Grille, overlooking the courtyard with Asian pheasants and colorful peacocks. Just 2 blocks from the famous River Walk, the hotel offers guests convenient access to the "Cradle of Texas Liberty." La Villita Historic Art Village, Hemisfair Park and Tower of Americas are also nearby. Shopping at Rivercenter Mall is convenient in downtime. Visitors will enjoy everything the hotel offers, including well-appointed guest rooms, a quiet landscaped pool, 17,000 square feet of event space, a state-of-the-art fitness center and close proximity to the Henry B. Gonzales Convention Center.

A room block with the Government Per Diem Rate ($121/night) will be held through **January 13, 2017**. Reservations requested after this date will be accepted based upon availability and subject to the hotel's prevailing rate. We encourage all conference attendees to make your hotel reservation early!

Attendees may register at the personal group web page listed below or they may call the reservations department at 1-800-228-9290. Please be sure to mention the group name "American Astronautical Society – Flight Mechanics Feb 2017" when making reservations in order to receive the group rate of $121 (or prevailing government per diem). Group arrival is 2/5/2017 and Group Departure is 2/9/2017. A limited number of rooms are available at the group rate 3 days pre/post group arrival and departure.

Group Reservation Page:

http://www.marriott.com/meeting-event-hotels/group-corporate-travel/groupCorp.mi?resLinkData=American%20Astronautical%20Society%20-%20Flight%20Mechanics%20Feb.%202017%5Esatpl%60fmafmaa%60120.00%60USD%60false%604%602/5/17%602/9/17%601/13/17&app=resvlink&stop_mobi=yes

Cancellations must be made 2 days in advance of intended arrival.

Complimentary internet access in guest rooms and meeting space is available to all conference attendees.

Arrival Information

Check-In and Checkout

- Check-in: 4:00 PM
- Check-out: 11:00 AM

Parking

Valet: $30/night

Self-parking is available on surface lots surrounding the hotel.

Hotel Services and Amenities

- All public areas non-smoking
- Beauty shop, nearby (referral at front desk)
- Buffet breakfast (fee)
- Cash machine/ATM
- Concierge Lounge
- Continental breakfast (fee)
- Foreign exchange, nearby
- Housekeeping service daily
- Laundry on-site, coin operated
- Local restaurant dinner delivery
- Mobility accessible rooms
- Newspaper delivered to room, on request
- Newspaper in lobby
- Room service, 6:00 AM-11:00 PM
- Safe deposit boxes, front desk
- Valet dry-cleaning
- Virtual Concierge Available

TRANSPORTATION INFO

AREA AIRPORT

San Antonio International Airport – SAT

Hotel direction: 9 miles South

The hotel does not provide shuttle service.

Estimated taxi fare (one way): $28

Driving directions from airport to hotel: Take Hwy. 281 (I-37) South. Take the Cesar Chavez exit. Go right on Cesar Chavez to Alamo. Take a right on Alamo. Take an immediate left on Arciniega. Hotel is on the corner of Alamo and Cesar Chavez streets.

AREA ATTRACTIONS

- The Alamo
- Alamodome
- El Mercado Mexican Market
- Arnesan River Theater/La Villita
- Hemisfair
- The Buckhorn Museum and the Texas Ranger Museum
- Fiesta Texas Amusement Park
- Sea World San Antonio
- Institute of Texan Cultures
- Brackenridge Park/Japanese Tea Gardens

For a more comprehensive Visitor's Guide, you can start at

http://www.marriott.com/hotels/local-things-to-do/satpl-marriott-plaza-san-antonio/

ADDITIONAL INFORMATION

SPEAKERS

Authors should have submitted a brief (approximately 50 words or 3 sentences) speaker's bio with their abstract submission. Author presentations (preferably in PDF format) will be submitted through a web-based system and are due by **Thursday February 2, 2017, 23:59:59 Eastern Time**. Authors are required to be in their session room 30 minutes prior to the start of their sessions. No speakers' breakfast will be served.

Authors are reminded that the deadline to upload pre-prints to the https://www.xcdsystem.com/aas/ website is before **January 25, 2017, 23:59:59 Eastern Time**.

VOLUNTEERS

Volunteers that would like to staff the registration table may sign up at the registration table.

PRESENTATIONS

Each presentation is limited to 15 minutes. An additional five minutes is allotted between presentations for audience participation and transition. Session chairs shall maintain the posted schedule to allow attendees the option of joining a parallel session. Each room is equipped with a laser pointer, an electrical outlet, and a video projector that can be driven by a computer. Presenters shall coordinate with their Session Chairs regarding the computing equipment, software, and media requirements for the session; however, *each presenter is ultimately responsible for having the necessary computer and software available to drive the presentation*. Microsoft PowerPoint and PDF are the most common formats.

"No-Paper, No-Podium" Policy: Completed manuscripts shall be electronically uploaded to the submission site before the conference, limited to 20 pages in length, and conform to the AAS conference paper format. If the completed manuscript is not contributed on time, it will not be presented at the conference. If there is no conference presentation by an author, the contributed manuscript shall be withdrawn.

Each author also acknowledges that he or she is releasing technical information to the general public and that respective papers and presentations have been cleared for public release. If any author of a paper is a US person (citizen or permanent resident), he or she acknowledges that the release of these data and content of the paper and presentation conforms to ITAR and are not on the USML. The information contained in these documents is neither classified, SBU, FOUO, nor proprietary to any sponsoring organization.

PREPRINTED MANUSCRIPTS

Physical copies of preprinted manuscripts are no longer available or required for the Space Flight Mechanics Meetings or the Astrodynamics Specialist Conferences. Electronic preprints are available for download at least 72 hours before the conference at https://www.xcdsystem.com/aas/ for registrants who use the online registration system. The hotel provides conference guests with complimentary wireless internet access in guest rooms and the conference meeting space. Registrants without an internet-capable portable computer, or those desiring traditional paper copies should download and print preprint manuscripts before arriving at the conference.

Conference Proceedings

All full registrants will receive a CD of the proceedings mailed to them after the conference (extra copies are available for $60 during the conference). However, the hardbound volume of *Advances in the Astronautical Sciences* covering this conference will be available to attendees at a reduced pre-publication cost, if ordered at the registration desk. After the conference, the hardbound proceedings will more than double in price, although authors will still receive a special 50% discount off the post-conference rate even if they delay their order until after the conference. Cost of Proceedings:

➢ Conference Rate	$290 domestic ($380 international)
➢ Post-Conference Rate	$600 (approx.)
➢ Authors (post-conference)	$300 (approx.)

Although the availability of hardcopy proceedings enhances the longevity of your work and elevates the importance of your conference contribution, please note that conference proceedings are not considered an archival publication. Authors are encouraged to submit their manuscripts after the meeting to one of the relevant journals, such as:

Journal of the Astronautical Sciences
Editor-in-Chief: Kathleen C. Howell
School of Aeronautics and Astronautics
3233 Armstrong Hall
Purdue University
West Lafayette, IN 47907
(765) 494-5786
howell@purdue.edu

Journal of Guidance, Control and Dynamics
Editor-in-Chief: Dr. Ping Lu, Iowa State University
Manuscripts can be submitted via: https://mc.manuscriptcentral.com/aiaa

Journal of Spacecraft and Rockets
Editor-in-Chief: Dr. Hanspeter Schaub, University of Colorado Boulder
Manuscripts can be submitted via: https://mc.manuscriptcentral.com/aiaa

Committee Meetings

Committee seating is limited to committee members and invited guests. Committee and subcommittee meetings will be held according to the schedule at the beginning of the program.

Conference Schedule

Feb 6, 2017La Villita A

01 Asteroid Missions I

Co Chair: Ryan Park

8:00 **AAS 17-221** **NASA Double Asteroid Redirection Test (DART) Low-Thrust Trajectory Concept**

Martin Ozimek, The Johns Hopkins University Applied Physics Laboratory; Justin Atchison, Johns Hopkins University Applied Physics Laboratory

Following a formal trade study, the Double Asteroid Redirection Test (DART) mission will use the NASA Evolutionary Xenon Thruster (NEXT) ion propulsion system. This will be the first in-space operation of the thruster. Low-thrust propulsion offers several advantages for DART, including lower launch vehicle costs via ride-sharing opportunities, the addition of an intermediate flyby asteroid, and optimization of the impact geometry. Despite these advantages, the change to a low-thrust baseline adds complexity to the trajectory analysis and flight operations. This paper will present the full scope of the baseline low-thrust trajectory concept that currently satisfies mission objectives and constraints.

8:20 **AAS 17-210** **The dynamical characteristics of heterogeneous asteroid 25143 Itokawa**

Lei Lan, Laboratory of Aerospace and Dynamics, School of Aerospace, Tsinghua University; Xianyu Wang, School of Aerospace Engineering, Tsinghua University

In this paper, we develop a methodology to study the periodic dynamics of irregular heterogeneous celestial body. It has been found that 25143 Itokawa may have varied internal structure reflected in the density variety of different areas, which may originate from the collision formation from multiple objects. We compare dynamical characteristics with that of homogeneous case. It is found that Jacobi-map, positions of equilibrium points, the types of bifurcations in the continuation of orbital family and the stability of periodic orbits near the heterogeneous body are different from those of homogeneous one.

8:40 **AAS 17-219** **Economical Spacecraft to investigate Temporarily Captured Objects near Earth**

Andrew Turner, SSL

Temporarily Captured Objects (TCOs) are small asteroids captured by lunar gravity assists (LGAs). A TCO resides in Earth orbit, possibly for several years, until destroyed by a lunar or an Earth impact, or re-ejected by an LGA into deep space. TCOs could contain valuable minerals, thus permitting asteroid mining to commence without the investment of launching to deep space and the long light-time delays associated with operations there. This paper discusses a proposed spacecraft orbiting the Sun-Earth L1 point to search for TCOs optically using reflected sunlight, also to undertake close passes by selected TCOs following the L1 Observatory phase.

9:00 AAS 17-206 NASA DOUBLE ASTEROID REDIRECTION TEST (DART) TRAJECTORY VALIDATION AND ROBUSTNESS

Bruno Sarli, Institute of Space and Astronautical Sciences; Martin Ozimek, The Johns Hopkins University Applied Physics Laboratory; Justin Atchison, Johns Hopkins University Applied Physics Laboratory; Jacob Englander, NASA Goddard Space Flight Center; Brent Barbee, NASA Goddard Space Flight Center

The Double Asteroid Redirection Test (DART) mission will be the first to test the concept of a kinetic impactor for planetary defense. The spacecraft will escape Earth, flyby (138971) 2001 CB21 for impart rehearsal, and impact the secondary body of of the (65803) Didymos system. This work focuses on the interplanetary trajectory design part of the mission with the validation of the baseline trajectory, performance comparison to other mission objectives, and assessment of the baseline robustness to missed thrust events. Results show a good performance of the selected trajectory for different mission objectives and robustness agains missed thrust

9:20 AAS 17-231 AN IMPROVED METHOD FOR CHARACTERIZING SMALL BODY DENSITY DISTRIBUTION

Siamak Hesar, University of Colorado; Daniel Scheeres, University of Colorado; Yu Takahashi, Jet Propulsion Laboratory; Jay McMahon, University of Colorado; Andrew French

An improved method for characterizing the density distribution of small bodies is presented in this paper. It utilizes a set of interior gravity field spherical harmonics expansions to place constraints on the likely distribution of the density inhomogeneities inside a body of mass. An interior spherical harmonics expansion is defined within the interior Brillouin sphere that extends down to the surface of a body of mass allowing it to be closer and more sensitive to the regional density dispersions. Furthermore, due to the way the interior expansion is constructed, using multiple expansion fields provides added geometry advantage to the problem.

9:40 **AAS 17-240** **A PRECISE MODEL FOR SMALL BODY THERMAL RADIATION PRESSURE ACTING ON SPACECRAFT: APPLICATIONS TO OSIRIS-REX SPACECRAFT**

Siamak Hesar, University of Colorado; Daniel Scheeres, University of Colorado; Jay McMahon, University of Colorado; Benjamin Rozitis, The Open University

A precise representation of small body surface thermal radiation pressure effects acting on orbiting spacecraft is discussed. The proposed model utilizes a general Fourier series expansion to compute small body surface thermal radiation pressure. Taking into account the shape and surface properties of spacecraft, this method allows for the precise representation of thermal radiation perturbation effects that may easily be used in the generation of precise orbit determination solutions. After presenting the general model, we provide an example application of the model for the OSIRIS-REx spacecraft in orbit about Asteroid (101955) Bennu.

10:00 **Morning Break**

10:20 **AAS 17-252** **Inflatable Sail for Asteroid Capture**

Samuel Ximenes, XArc Exploration Architecture Corp; Barney Gorin, GoVentures, Inc.; Roy Hartfield, Auburn University; David Cicci, Auburn University; Bruce Tatarchuk, Auburn University; Marek Teichmann, CMLabs Simulations Inc.

Asteroid capture missions are currently being addressed by NASA with its Asteroid Redirect Mission (ARM), and by various commercial space mining companies for resource mining operations. Addressed is a unique and innovative approach for robotically capturing an irregularly shaped asteroid, spinning in its lowest energy state. The concept permits capture of higher-aspect ratio asteroids outside of a mean 4-10m diameter. The concept employs an innovative, large "Sail" capture mechanism. The Sail is deployed beyond the spacecraft envelope and can adapt to an asteroid with a long dimension significantly larger than 10 meters.

10:40 **AAS 17-257** **SENSITIVITY OF THE ASTEROID REDIRECT ROBOTIC MISSION (ARRM) TO LAUNCH DATE AND ASTEROID STAY TIME**

Melissa McGuire, NASA GRC; Nathan Strange, Jet Propulsion Laboratory / California Institute of Technology; Laura Burke, NASA Glenn Research Center; Steve McCarty, NASA Glenn Research Center; Min Qu, AMA; Haijun Shen, Analytical Mechanics Associates, Inc.; Matthew Vavrina, a.i. solutions

In order to understand the sensitivity of NASA's Asteroid Redirect Robotic Mission (ARRM) reference trajectory to asteroid stay time and launch date, a series of analyses have been performed to assess the impact that variations in 2008 EV5 stay time have on the returned boulder mass and allowable spacecraft dry mass. The results of these analyses as well as the ground rules and assumptions of the current ARRM reference trajectory are documented in this paper.

11:00 AAS 17-258 Dynamical structures for the study of irregular gravity fields
Simon Tardivel, University of Colorado Boulder; Daniel Scheeres, University of Colorado

This paper introduces dynamical structures relevant for the study of the effective gravity field of small bodies. The variety of shapes that small bodies display hinders the analytical study of their gravity fields. Yet, they all exhibit the same fundamental dynamical structure. Introducing the z^* plane, the ridge line and its equilibrium points, and the potential barrier, this work allows to generalize previous analytical studies on simpler fields (e.g. CR3BP). These dynamical structures are defined, described, and computed for different bodies. They are useful for the description of the dynamical environment of the small body, e.g. equilibrium points and entrapment.

11:20 AAS 17-469 Modelling Irregular Small Bodies Gravity Field via Extreme Learning Machines
Roberto Furfaro, The University of Arizona; Richard Linares, University of Minnesota; Vishnu Reddy, University of Arizona; Jules Simo, University of Central Lancashire; Lucille Le Corre, Planetary Science Institute

In this paper, we propose a new methodology to model the gravity field of an irregular small body for a fast, accurate and efficient calculation of the gravitational acceleration as function of the relative position around the small body of interest.

11:40 AAS 17-214 Multi-Objective Optimization of Spacecraft Trajectories for Small-Body Coverage Missions
David Hinckley, University of Vermont; Jacob Englander, NASA Goddard Space Flight Center; Darren Hitt, University of Vermont

Visual coverage of surface elements of a small-body requires multiple images to be taken that meet many requirements on their viewing angles, illumination angles, times of day, and combinations thereof. Designing trajectories capable of maximizing total possible coverage may not be useful since the image target sequence and the feasibility of said sequence given the rotational limitations of the spacecraft are not taken into account. This work presents a means of optimizing, in a multi-objective manner, surface target sequences that account for such limitations.

Feb 6, 2017La Villita B

02 Trajectory Optimization I

Co Chair: Atri Dutta

8:20 **AAS 17-224** **Improved Propulsion Modeling For Low-Thrust Trajectory Optimization**
Jeremy Knittel, NASA Goddard Space Flight Center; Jacob Englander, NASA Goddard Space Flight Center; Martin Ozimek, The Johns Hopkins University Applied Physics Laboratory; Justin Atchison, Johns Hopkins University Applied Physics Laboratory; Julian Gould, Johns Hopkins University

The propulsion and power characteristics of a low-thrust spacecraft are major drivers in the design of the optimal trajectory. The more accurate the power and propulsion modeling, the more accurate the optimal trajectory will be. In this work, we discuss new techniques to improve the accuracy of propulsion modeling in low-thrust trajectory optimization while maintaining the smooth derivatives that are necessary for a gradient-based optimizer. The resulting model is significantly more realistic than the industry standard and performs well inside an optimizer. A variety of deep-space trajectory examples are presented.

8:40 **AAS 17-243** **NEAR OPTIMAL FINITE-TIME FEEDBACK CONTROL SYNTHESIS USING THE SDRE-BASED APPROACH EXTENDED FOR NONLINEAR TERMINAL HYPERSURFACES**
Rajnish Sharma, University of Maryland Eastern Shore; George York, United States Air Force Academy

This paper presents a novel development to synthesize **finite-time near optimal feedback control for nonlinear systems with nonlinear terminal constraints such as hypersurfaces**. To design such terminal feedback controllers, the SDRE-based approach is extended for the fixed-final continuous-time optimal control problem via solving the governing Hamilton-Jacobi-Bellman equation subject to the pseudo-linear system with general terminal hyperplanes. Further, to fit this novel extension into a class of terminal hypersurfaces, the procedure to obtain approximated tangent hyperplanes is introduced to construct suboptimal feedback control. To establish the new methodology and its performance, numerical investigations including examples in space applications are illustrated with details.

9:00 **AAS 17-253** **Low-Thrust Many-Revolution Trajectory Optimization via Differential Dynamic Programming and a Sundman Transformation**

Jonathan Aziz, University of Colorado Boulder; Jeff Parker, University of Colorado; Daniel Scheeres, University of Colorado; Jacob Englander, NASA Goddard Space Flight Center

Low-thrust trajectories about planetary bodies often exhibit a high count of orbital revolutions. Directing the thrust vector over many revolutions produces a cumbersome number of decision variables for any conventional optimization strategy. This paper demonstrates the tractability of low-thrust trajectory optimization about planetary bodies by applying a Sundman Transformation to change the independent variable of the spacecraft equations of motion to an orbit anomaly and performing the optimization with differential dynamic programming. Fuel-optimal geocentric transfers are shown in excess of 1000 revolutions while subject to Earth's J_2 perturbation and lunar gravity.

9:20 **AAS 17-281** **Asteroid Deflection with Safe Harbors Found via Numerical Optimization**

Bruce Conway, Univ of IL; Siegfried Eggl, IMCCE Observatoire de Paris; Daniel Hestroffer, IMCCE Observatoire de Paris

If feasible, given the warning time of a hazardous asteroid approach, to “safely park” the asteroid in a region of phase space that does not yield a significant future impact risk (i.e. a “safe harbor”) with the Earth, this should certainly be done. In this work a metaheuristic method is used to optimize all of the relevant mission parameters for a spacecraft to deflect an asteroid via impact. The objective of the numerical optimizer is to maximize the deflection obtained while assuring that subsequent close approach distances of the asteroid to the Earth are only increased by the initial deflection.

9:40 **AAS 17-303** **Combining Non-Linear Programming and Hyperheuristic Algorithms for Low-Thrust Trajectory Optimization**

Lake Singh, The Aerospace Corporation; Jose Guzman, The Aerospace Corporation; Chris Ranieri, The Aerospace Corporation; Demyan Lantukh, The Aerospace Corporation; Gregory Fruth, The Aerospace Corporation

This work reports on an effort to drive an non-linear programming (NLP) optimizer with a hyperheuristic MOEA in order to mitigate workflow challenges associated with traditional iterative, constructive NLP approaches. Calculus of variations and Non-linear programming approaches can efficiently and rapidly produce optimized low-thrust trajectories in complex design spaces. However, for non-globally convex function spaces, these approaches optimize locally. In contrast, hyperheuristic many-objective evolutionary algorithms efficiently identify globally optimal regions of the design space, even in the presence of discontinuities and large regions of infeasibility. Coupling hyperheuristics and NLP helps users avoid time consuming iteration by passing the task of construction to the hyperheuristic.

10:00 **Morning Break**

10:20 **AAS 17-447** **Resonance Orbit Generation for Global Optimization Seeding**
Deivn Bunce, University of Illinois at Urbana Champaign; Ryne Beeson, University of Illinois at Urbana-Champaign; Victoria Coverstone, University of Illinois at Urbana-Champaign

The University of Illinois at Urbana-Champaign has been focused on developing a computationally efficient automated global optimization tool for solution of spacecraft in the three-body problem. Resonance orbits show significant potential for mission trajectory design. The goal of this paper is to explore the benefits and challenges of incorporating resonance orbits and their manifold structures into an automated global optimization framework that already makes explicit use of other pertinent dynamical structures of the circular restricted three-body problem. This includes a trade-off study associated with seeding optimal control solutions based on states along resonance orbits.

10:40 **AAS 17-453** **A Multiple-Shooting Differential Dynamic Programming Algorithm**
Etienne Pellegrini, The University of Texas at Austin; Ryan Russell, The University of Texas at Austin

The Hybrid Differential Dynamic Programming algorithm is a second-order optimal control algorithm, which applies Bellman’s Principle of Optimality for local optimization. The algorithm uses State-Transition Matrices to decouple the optimization and dynamics, and successive optimization of quadratic approximations. The present paper extends the HDDP algorithm to use a multiple-shooting structure, in order to help alleviate large sensitivities present in highly nonlinear problems, to improve the algorithm’s robustness to initial guesses, and to increase the potential for a parallel implementation. The necessary theoretical developments are presented, and numerical results are shown for a variety of optimal control problems, including the low-thrust spacecraft trajectory problem.

11:00 **AAS 17-476** **A Novel State Space Representation of Particle Swarm Optimization Dynamics**
Michael Johnson, University of New Hampshire; May-Win Thein, University of New

Hampshire

centParticle Swarm Optimization (PSO) is an optimization technique that has risen to recent popularity. The method was conceived by trying to mimic swarms of animals. There is a bevy of research demonstrating the viability of PSO on benchmarks and in real-world applications. While the performance of PSO is promising, it depends on configuration parameters. Since the algorithm was developed from empirical observation, there does not currently exist a strong theoretical framework to inform the selection of these parameters. Presented here is a derivation of a State Space Dynamics representation which allows for the use of existing dynamical system analysis methods.

11:20 AAS 17-511 Accommodating Measurement Uncertainty in the Optimization of Space Flight Trajectories

Alan Zorn, Stanford University; Matt West, University of Illinois

Equality constraints in trajectory optimization are frequently handled as exact in space flight optimization. Frequently, however, the constraints are not known exactly, perhaps due to measurement uncertainty. In a recent paper by the authors, it is shown how “soft” boundary conditions can be accommodated in a very natural way by solving the deterministic optimization problem as a maximum a posteriori (MAP) estimation problem. In this paper, we use this method to solve three problems in space flight mechanics which demonstrate how the approach might improve cost or computational performance and reveal new relationships.

11:40 AAS 17-273 Atmospheric Modeling Using Accelerometer Data During Mars Atmosphere and Volatile Evolution (MAVEN) Flight Operations

Robert Tolson, National Institute of Aerospace; Rafael Lugo, Analytical Mechanics Associates, Inc.; Darren Baird; Alicia Dwyer Cianciolo, NASA; Stephen Bougher, University of Michigan; Richard Zurek

The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft is a NASA orbiter designed to explore the Mars upper atmosphere. MAVEN has performed several Deep Dip campaigns in which the orbit periapsis was lowered to an altitude range of 115 to 135 km. MAVEN accelerometer data were used during mission operations to estimate atmospheric parameters. These estimates were used to aid the MAVEN navigation team in planning maneuvers to raise and lower periapsis during Deep Dip operations. This paper describes the processes used to reconstruct atmosphere parameters from accelerometer data and presents comparisons between model navigation-derived values.

Feb 6, 2017La Villita C

03 Rendezvous and Proximity Operations I

Co Chair: Andrew Sinclair

8:00 **AAS 17-229** **Autonomous Shape Determination Using Flash-Lidar Observations**
Benjamin Bercovici, University of Colorado Boulder; Jay McMahon, University of Colorado

Flash-Lidar sensors provide valuable observations usable to determine the shape model of a target, but the collected data is too dense to be used as state model parameters. Algorithms autonomously constructing an a-priori from the observations are thus needed. To this end, a feature extractor autonomously computing an apriori facet-vertex shape model from the observations was constructed. A batch estimator was used to determine the model parameters from the a-priori and the observations. This framework has been successfully tested on noise-free observations. Current work focuses on deriving heuristics enabling this framework to process noisy observations.

8:20 **AAS 17-246** **Angles-only Initial Relative Orbit Determination for Space Rendezvous Based on Virtual Distribution Method**
Baichun Gong, Northwestern Polytechnical University; Jianjun Luo; Jianping Yuan; Jinglang Feng

This research develops a closed-form solution to the angles-only initial relative orbit determination problem for space rendezvous where a method of mixed spacecraft dynamics for virtual spacecraft formations produces range observability. And state observability analysis and covariance analysis are conducted. Then, a two-body Monte Carlo simulation system is used to verify the feasibility and evaluate the performance of the closed-form relative state estimation algorithms. The sensitivity of the solution accuracy to the formation geometry, camera accuracy and the time-interval between measurements is presented and discussed.

8:40 **AAS 17-263** **Initial Pose Estimation using PMD Sensor during the Rendezvous Phase in On-Orbit Servicing Missions**
Ksenia Klionovska, German Aerospace Center; Heike Benninghoff, German Aerospace Center

On-orbit failures, space debris and orbital crowding are the prerequisites for the high demand in the field of On-Orbit Servicing missions. In order to remove or repair the satellite, it is necessary estimate the pose of the target to ensure the safe autonomous approach .The present work represents the model-based initial pose estimation technique using the relatively new type of optical sensor, namely PMD sensor. The performance of the algorithm is investigated by comparing the results with a ground truth data obtained from the European Proximity operations simulator for Rendezvous and Docking purposes.

9:00 AAS 17-272 Approaches and Fly-Arounds for Spacecraft Proximity Operations
John Goodman, Odyssey Space Research, LLC

Proximity operations (range < 2 km) includes an approach trajectory leading to chaser spacecraft docking or robotic grappling with a target spacecraft. For current human and robotic spacecraft, low energy approaches along the target spacecraft velocity or radius vectors are preferred over higher energy inertial approaches. A fly-around of the target by the chaser may be performed to reach a final approach axis or to perform visual inspection. Back-out and separation (nominal or contingency) are also a part of proximity operations. A partial fly-around may be flown to reach the location of a separation burn.

9:20 AAS 17-330 Velocity-Free Control of Spacecraft Body-Fixed Hovering Around Asteroids
Haichao Gui, Ryerson University; Anton de Ruiter, Ryerson University

This paper addresses the body-fixed hovering of a spacecraft about uniformly rotating asteroids without translational velocity measurements. A nonlinear high-gain observer is proposed to estimate the velocity of the spacecraft and the unknown perturbations due to highly uncertain dynamical environments around asteroids. With the velocity and perturbation estimates, a hovering controller is then designed to stabilize the spacecraft to a stable fixed position with respect to the asteroid. The stability of the entire closed-loop system is shown by Lyapunov theory and numerical simulations are presented to verify the effectiveness of the proposed methods.

9:40 AAS 17-379 GUIDANCE SOLUTIONS FOR SPACECRAFT PLANAR REPHASING AND RENDEZVOUS USING INPUT SHAPING CONTROL
Margaret Lawn, University of Florida; Giuseppe Di Mauro, University of Florida; Riccardo Bevilacqua, University of Florida

Small satellites formation flying has been attracting growing interest. While economical to design and to launch, they have limited computational capability and propellant capacity. Thrusters must generally have a small form factor and use minimal propellant, often operating only in on/off configurations and with a few set force magnitudes. Therefore, efficient relative orbit control techniques must be developed to satisfy low-thrust constraints without reducing performance accuracy or straining the limited computational power of the small on-board systems. This paper presents analytical guidance solutions for orbital planar spacecraft rephasing and rendezvous using in-plane continuous low-thrust profiles derived from input shaping theory.

10:00 Morning Break

10:20 AAS 17-418 Convex optimization for proximity maneuvering of spacecraft with a robotic manipulator

Josep Virgili-Llop, Naval Postgraduate School; Costantinos Zagaris, Naval Postgraduate School; Richard Zappulla, Naval Postgraduate School; Andrew Bradstreet, Naval Postgraduate School; Marcello Romano, Naval Postgraduate School

The dynamic complexities of spacecraft-manipulator systems complicate the optimization of their maneuvers. We propose to optimize these maneuvers by solving a collection of simpler convex optimization problems. First, the maneuver is divided into two simultaneously occurring maneuvers: the system-wide translation and the internal re-configuration. These two sub-maneuvers are individually and sequentially optimized. For each of the two optimization problems a sequential convex optimization approach is used to overcome the presence of non-convex inequality an nonlinear equality constraints. For the line-of-sight constraints, a new semidefine formulation is introduced. The result: an optimization procedure that is potentially suitable for on-board implementation.

10:40 AAS 17-419 Analysis of Spacecraft Planar Docking with Rotating Body in Close Proximity

Costantinos Zagaris, Naval Postgraduate School; Marcello Romano, Naval Postgraduate School

Spacecraft rendezvous and proximity missions have been addressed in several past publications, focusing
on many different aspects of the problem. This paper investigates a scenario where the target spacecraft
is rotating on a plane, at a constant rate, and the chaser spacecraft is on the same plane within close
proximity. The controllability characteristics of the problem are analyzed for both unbounded and bounded
control inputs. The goal of this research is to identify a reachable set of initial conditions, from which the
chaser can successfully dock with the target.

11:00 AAS A MULTI-MODE RENDEZVOUS CONTROL ALGORITHM FOR A

17-454 SATELLITE UTILIZING STEREO CAMERA BASED PROXIMITY SENSOR

Burak Akbulut, Turkish Aerospace Industries Inc.; Kağan Ataalp, Turkish Aerospace Industries Inc.; Mehmet Can Ünlü, TUSAŞ-Türk Havacılık ve Uzay Sanayii A.Ş.

Rendezvous missions are key milestones for space technology; however, they require dedicated sensors for realization. Different types of sensors are currently available for this purpose, involving LIDAR and Vision based ones. In the current study a stereo-camera based sensor is utilized. This particular sensor already has a proof-of-concept model implemented. Utilizing a mathematical model of this sensor, a hypothetical rendezvous mission would be developed involving a chaser and a target satellites. Dedicated control algorithm architecture will be built, including multiple control modes.

11:20 AAS 17-496 Nonlinear Model Predictive Control for Spacecraft Rendezvous and Docking with a Rotating Target

Hyeongjun Park, Naval Postgraduate School; Richard Zappulla, Naval Postgraduate School; Costantinos Zagaris, Naval Postgraduate School; Josep Virgili-Llop, Naval Postgraduate School; Marcello Romano, Naval Postgraduate School

In this paper, we propose a nonlinear model predictive control (MPC) approach in spacecraft rendezvous and docking with a rotating target and experimentally evaluate the performance on a physical test bed in real time. The constraints on thrust and approach velocity are considered for hardware limitations and safe docking. In addition, different constraints on chaser spacecraft positioning are analyzed and compared for rotating target cases. Constraints on the terminal docking corridor are also imposed in the MPC framework. The experimental results are evaluated using comparison metrics including fuel consumption, elapsed maneuvering time, and computational time of IPOPT (Interior Point OPTimizer).

Feb 6, 2017Pavo Real

04 Space Situational Awareness I

Co Chair: Matthew Wilkins

8:00 AAS 17-216 Debris Avoidance Maneuvers for Spacecraft in a Cluster

Elad Denenberg, Technion – Israel Institute of Technology; Pini Gurfil, Technion – Israel Institute of Technology

In this paper three techniques for finding optimal maneuvers under the constraints of cluster keeping are developed. The first is an execution of an additional cluster keeping maneuver at the debris time of closest approach, the second is a global all-cluster maneuver, and the third is a fuel-optimal maneuver, which incorporates the cluster keeping constraints. The first methodology proves to be the most efficient. The global maneuver is rather fuel-expensive. The last method proves to be useful at certain timings, and is a compromise between fuel consumption, and the number of maneuvers.

8:20 AAS 17-271 TIME DEPENDENCE OF COLLISION PROBABILITIES DURING SATELLITE CONJUNCTIONS

Doyle Hall, Omitron, Inc.; Matthew Hejduk, Astrorum Consulting LLC; Lauren Johnson, Omitron

The NASA Conjunction Assessment Risk Analysis team has implemented new software to calculate the probability of collision (P_c) for Earth-orbiting satellites. The algorithm can employ complex dynamical models, and account for non-linear trajectories as well as position and velocity uncertainties. This “3D P_c” method provides estimates of variations in the probability rate, R_c. For close-proximity satellites, $R_c$can show multiple peaks that blend with one another. For isolated conjunctions, R_c analysis provides the means to identify and bound times of peak collision risk. Archive analysis demonstrates that the commonly used “2D P_c” approximation can occasionally provide very inaccurate estimates.

8:40 AAS 17-318 Intensity Correlation Imaging of Space Objects Via Noise Reducing Phase Retrieval

David Hyland, Texas A&M University

Intensity Correlation Imaging (ICI) offers a relatively inexpensive and robust technique to image space objects at fine angular resolution, but has been limited to bright sources. This paper describes details the application of recently developed noise reducing phase retrieval algorithms to ICI. Coherence magnitude estimation via photon arrival coincidence counting, and the corresponding statistics, are explained. The phase retrieval algorithms are extended so as to incorporate *a priori* information, such as object size or outline estimates. More complex data can be encoded by choice of the integration time for each baseline. By this stratagem, the effective SNR is greatly increased.

9:00 AAS 17-332 POLICY GRADIENT APPROACH FOR DYNAMIC SENSOR TASKING APPLIED TO SPACE SITUATIONAL AWARENESS

Richard Linares, University of Minnesota; Roberto Furfaro, The University of

Arizona

This paper studies the sensors tasking and management problem for optical Space Object (SO) tracking. The tasking problem is formulated as Markov Decision Process (MDP) and solved using Reinforcement Learning (RL). This RL problem is solved using actor-critic policy gradient approach. This approach is used to find the optimal policy for tasking optical sensors to estimate SO orbits. The reward function is based reducing the uncertainty for the overall catalog to a given upper bound. The reward is negative as long as a SO exist that is about the desired catalog uncertainty.

9:20 AAS 17-354 Method of Equivalent Areas Used in the Analytical Formulation of the Probability of Collision

Ken Chan, Chan Aerospace Consultants

This paper discusses the method of equivalent areas introduced in the analytical formulation of the probability of collision between two orbiting objects. This principle was applied to approximate the elliptical area of integration in an isotropic two-dimensional Gaussian probability density distribution by a circular one with the same area and the same centroid. The results so obtained agreed to three or four significant figures with detailed computations using realistic values of the covariance and miss distance of spacecraft encounters. The reason for this extraordinary agreement is because all odd order and some even order terms vanish in a Taylor's expansion.

9:40 AAS 17-390 Orbital Error Propagation Analysis using Directional Statistics for Space Objects

John Kent, University of Leeds; SHAMBO BHATTACHARJEE, University of Leeds; Islam Hussein, Applied Defense Solutions; Moriba Jah, University of Arizona

As increasing numbers of optical line-of-sight observations become available for space objects, problem of representing the uncertainty efficiently and accurately becomes more challenging. The motion of a space object in orbit about the earth is described by Newtonian mechanics. More specifically, if measurements for the position and velocity at an initial time are available up to Gaussian noise, then point clouds are typically used to describe the propagated uncertainty at later times. We use a version of the Fisher-Bingham-Kent distribution from directional statistics to describe succinctly the angular part of the position vector at later times.

10:00 **Morning Break**

10:20 **AAS 17-434** **Dynamic Coordinate Systems for Faster Orbital State Propagation**
Blair Thompson, Applied Defense Solutions; Islam Hussein, Applied Defense Solutions; Thomas Kelecy, Applied Defense Solutions

New coordinate systems have been developed for faster state propagation without changing integration method or order. This enhancement could find application in autonomous spacecraft operations, or wherever ephemerides must be autonomously generated. Classical state propagation requires the integration of six first-order equations which are generally out of phase. The integration must proceed with a smaller step size to preserve overall accuracy. The coordinates of the newly developed systems were chosen to be slow changing and more in phase, allowing a larger step size. Initial testing shows propagation speed is significantly increased, especially for low eccentricity orbits.

Feb 6, 2017La Villita A

05 Launch and Landing Operations

Co Chair: David Spencer

13:30 **AAS 17-220** **Trajectory Analysis for the Unicorn small Single-Stage-to-Orbit Launch Vehicle**
Andrew Turner, SSL

Many small launchers are currently under development to address the growing miniature spacecraft market including Cubesats and other small vehicles. All such launchers employ conventional LOX-kerosene propellants in a Two Stage to Orbit (TSTO) configuration. This paper provides trajectory analysis and vehicle design background for a LOX-liquid hydrogen approach which enables a Single Stage to Orbit (SSTO) launcher, with attendant savings in production and other costs, including employment of a single large engine for all major maneuvers. SSTO avoids the in-flight stage separation and engine ignition under TSTO with its associated design complexities and failure modes, as will be discussed.

13:50 **AAS 17-274** **Launch Vehicle Ascent Trajectory Simulation Using The Program to Optimize Simulated Trajectories II (POST2)**
Rafael Lugo, Analytical Mechanics Associates, Inc.; Jeremy Shidner, Analytical Mechanics Associates, Inc.; Richard Powell, AMA; Steven Marsh, Analytical Mechanics Associates, Inc.; James Hoffman, Analytical Mechanics Associates,

Inc.; Daniel Litton, NASA; Terri Schmitt, NASA Marshall Space Flight Center

The Program to Optimize Simulated Trajectories II (POST2) has been continuously developed for over 40 years and has been used in many flight and research projects. Recently, there has been an effort to improve the POST2 architecture by promoting modularity, flexibility, and ability to support multiple simultaneous projects. The purpose of this paper is to provide insight into the development of trajectory simulation in POST2 by describing methods and examples of various improved models for a launch vehicle liftoff and ascent.

14:10 AAS 17-399 Reusable Booster Launch Vehicle Optimal Branching Trajectories
Demyan Lantukh, The Aerospace Corporation; Shaun Brown, The Aerospace Corporation

Reusable boosters promise cost advantages for launch vehicles but also present significant challenges for trajectory optimization. The trajectories and parameters of both reusable booster stage and disposable upper stage are solved simultaneously using direct transcription optimal control techniques. The combined approach enables efficient tradeoff between the stages and demonstrates key features of the resulting trajectories. Specialized dynamics and constraints are applied in GPOPS-II to a variety of vehicles – boost-back, glide-back and mixed boost-glide-back first stage return – targeting various orbits – LEO, Polar, and GTO. The demonstrated method allows end-to-end simultaneous optimization of boost to orbit and return of the first stage.

14:30 AAS 17-520 DESIGN ROCKET VERTICAL LANDING GUIDANCE LAW USING A GAUSS POINT DISCRETE CONVEX PROGRAMMING
Zhang Zhiguo, Tsinghua University; Guangyou Geng; Menglun Yu; Ying Ma; Mingwei Yin

A Gauss point discrete convex programming is used to design the rocket's vertical recovery landing guidance law. A resulting SOCP problem is solved in both entry flight phase and powered descent phase, and a successive linearization relaxation technique is used to deal with highly nonlinear constrained trajectory optimization problem. Through choosing very few LGL points, a piecewise Lagrange interpolation approximation of the control input is used to discrete original problem into a parametric optimization problem. Finally, the influence on the guidance precision of various disturbances is considered, and the results show this method has high solving efficiency and strong adaptability.

14:50 AAS 17-254 ENTRY, DESCENT, AND LANDING GUIDANCE AND CONTROL APPROACHES TO SATISFY MARS HUMAN MISSION LANDING CRITERIA

Alicia Dwyer Cianciolo, NASA; Richard Powell, AMA

Precision landing on Mars is a challenge. All Mars lander missions prior to the Mars Science Laboratory resulted in landing ellipses on the order of 100s of kilometers. To land humans on the surface of Mars will require orders of magnitude improvement in landing accuracy. The current Evolvable Mars Campaign human-class landing requirement is 50 m from a specified target. This paper will present the challenges of a human scale low L/D vehicle to use bank angle control to satisfy the EMC landing requirement. It will also present an alternative guidance and control approach, called Direct Force Control.

15:10 AAS 17-370 Landing on Small Bodies Trajectory Design, Robust Nonlinear Guidance and Control

Eric Joffre, Airbus Defence and Space Ltd; Mattia Zamaro, Airbus Defence and Space; Pedro Simplicio, Univresity of Bristol; Barbara Richardson, UK Space Agency; Nuno Silva, Airbus Defence and Space Lrd; Andres Marcos

While common Descent and Landing strategies involve extended periods of forced motion, significant fuel savings could be achieved by exploiting the natural dynamics in the vicinity of the target. However, small bodies are characterised by perturbed and poorly known dynamics environments, calling for autonomous guidance, navigation and robust control. Airbus DS and the University of Bristol have been contracted by UKSA to investigate the optimisation of landing trajectories, including novel approaches from dynamical systems theory, and robust nonlinear control techniques. This paper presents and benchmarks these techniques, with an application to the strategic case of a mission to Phobos.

Feb 6, 2017La Villita B

06 Trajectory Design

Co Chair: Jeff Parker

13:30 AAS 17-372 Trajectory Planning of Approaching Non-cooperative Targets Based on Gauss Pseudospectral Method

Heng Shi, Tsinghua University; Jihong Zhu, Tsinghua University

When approaching a non-cooperative spacecraft, its status and information are usually unable to get, besides there may exist obstacles. This paper constructs a continuous model to investigate the trajectory planning method. Attitude of chaser and relative position are set as state variable. The path of avoiding obstacles is considered as constraint. Combined with terminal constraints and performance indicators, the parametric optimization model of algebraic constraints is established. Gauss pseudospectral method is deployed to discretize the continuous model. The problem is solved by sequential quadratic programming. Calculation and simulation module is developed to prove the feasibility of the method.

13:50 AAS 17-286 Trajectory Design for a Cislunar CubeSat Leveraging Dynamical Systems Techniques: The Lunar IceCube Mission

Natasha Bosanac, Purdue University; Andrew Cox, Purdue University; Kathleen Howell, Purdue University; David Folta, NASA Goddard Space Flight Center

Lunar IceCube is a 6U CubeSat that is designed to detect and observe lunar volatiles from a highly inclined orbit. This spacecraft, equipped with a low-thrust engine, will be deployed from the upcoming Exploration Mission-1 vehicle in late 2018. However, significant uncertainty in the deployment conditions for secondary payloads impacts both the availability and geometry of transfers that deliver the spacecraft to the lunar vicinity. A framework that leverages dynamical systems techniques is applied to a recently updated set of deployment conditions and spacecraft parameter values for the Lunar IceCube mission, demonstrating the capability for rapid trajectory design.

14:10 AAS 17-344 Multi-goal trajectory planning for redundant space robot

Suping Zhao; zhanxia zhu; Bruno Siciliano; Alejandro Gutiérrez-Giles; Jinglang Feng; Jianjun Luo

The multi-goal trajectory planning problem(MTPP) for redundant space robot is studied in this paper, which is converted into a bilevel programming problem. The aim of the first level is to search for an optimal path that pass through the predefined waypoints. Based on the optimal path got in the first level, the aim of the second part is to search for the appropriate joints movements corresponding to the optimal path. Two-layer-based heuristic algorithm is employed to solve the bilevel programming problem and find an optimal trajectory with smooth joints movements.

14:30 AAS 17-356 REACHABLE DOMAIN OF SPACECRAFT WITH A SINGLE NORMAL IMPULSE

Junhua Zhang; Jianping Yuan; Wei Wang; Jinglang Feng; zhanxia zhu

The reachable domain for spacecraft with a single normal impulse is studied. The problem is addressed in an analytical approach by analyzing for either the initial maneuver point or the impulse magnitude being arbitrary. The trajectories are considered lying in the intersection of a plane and an ellipsoid of revolution, whose family can be determined analytically. Moreover, the impulse constraints and time constraints are also considered while formulating the problem. Using the presented methodology, the "high consumption areas" near the unreachable domain are discussed. Finally, several numerical analyses are performed in MATLAB to show the geometry of the reachable domain.

14:50 **AAS 17-438** **Strategies for Low-Thrust Transfers from Elliptical Orbits to Geostationary Orbit**

Craig Kluever, University of Missouri; Scott Messenger, Northrop Grumman Corporation

Low-thrust transfers to geostationary-equatorial orbit (GEO) will likely start in energetic orbits in order to reduce the transfer time. One attractive option is to initiate the transfer from a geostationary-transfer orbit (GTO). While the low-thrust GTO-GEO trajectory-optimization problem is well understood, the spacecraft's interaction with trapped particles in the Van Allen radiation belts has not been accurately modeled by researchers in the space flight community. This paper merges the low-thrust transfer problem with state-of-the-art models for the radiation environment and subsequent solar-cell degradation. The goal is to determine orbit-transfer scenarios that minimize power loss and the radiation-shielding mass.

15:10 **AAS 17-481** **Optimal Trajectory Design and Control of a Planetary Exploration Rover**

Kamesh Subbarao, The University of Texas at Arlington; Ameya Godbole, The University of Texas at Arlington; Paul Quillen, The University of Texas at Arlington; Veerapaneni Murali

This paper considers the design of a reference trajectory for a rover located in a constrained, obstacle laden environment. The paper essentially tackles the problem of trajectory re-design when some key parameters related to the vehicle capability such as maximum achievable acceleration change either due to loss of power or mechanical uncertainty. If a goal location has to be reached, the vehicle needs to re-plan it optimal trajectory and will mostly follow a longer time trajectory. Of particular interest to this work is the minimum jerk optimal trajectory for which an analytical result can be derived.

15:30 **Afternoon Break**

15:50 **AAS 17-510** **A NOVEL METHODOLOGY FOR FAST AND ROBUST COMPUTATION OF LOW-THRUST ORBIT-RAISING TRAJECTORIES**
Suwat Sreesawet, Wichita State University; Atri Dutta, Wichita State University

All-electric spacecraft makes numerous revolutions during the orbit-raising to the geosynchronous equatorial orbit. This paper presents a new mathematical formulation to describe the dynamics of the spacecraft under the action of continuous thrust. Furthermore, it presents a new optimization framework that considers the proposed dynamic model to solve a sequence of optimization sub-problems for rapid and robust generation of the low-thrust orbit-raising trajectories. It is considered that the spacecraft does not thrust in the shadow of the Earth. Numerical results for different orbit-raising mission scenarios are presented to illustrate the performance of the algorithm.

Feb 6, 2017La Villita C

07 Dynamical Systems Theory Applied to Space Flight

Co Chair: Kathleen Howell

13:30 **AAS 17-464** **Reachability Subspace Exploration using Continuation Methods**
Julian Brew; Marcus Holzinger, Georgia Institute of Technology

Reachability manifold computation suffers from the curse of dimensionality and for large state spaces is computationally intractable. This paper examines the use of continuation methods to address this issue by formulating the reachability subspace manifold calculation into a number of initial valued problems. As a result of computing the reachability manifold for a subspace of interest, an exponential improvement in computational cost occurs. This concept is applied to a position subspace reachability problem of a spacecraft in a Keplerian orbit under maximum thrust constraints.

13:50 **AAS 17-504** **EVALUATING QUASIPERIODIC TRAJECTORIES IN THE VICINITY OF IRREGULAR SMALL BODIES WITH ENTROPY**
Yanshuo NI, Tsinghua University; Konstantin Turitsyn; Hexi Baoyin, Tsinghua University; Junfeng Li

Discrete Fourier Transform is used to analyze trajectories since qua-siperiodic motion can be basically thought of as a mixture of periodic mo-tions of several different fundamental frequencies. Quasiperiodic trajectories with better regularity show more concentrated on their frequency dis-tribution. Having introduced concept of entropy, the concentration of fre-quency can be analyzed quantitatively and the results confirm that a qua-siperiodic trajectory whose frequency distribution is more concentrated af-ter DFT has a higher entropy, that is, the motion is more organized. This is the first time in the field of orbital dynamics evaluating the quality of quasiperiodic trajectories by quantitative analysis.

14:10 **AAS 17-515** **Survey of Mars Ballistic Capture Trajectories Using Periodic Orbits**
Diogene Alessandro Dei Tos, Politecnico di Milano; Ryan Russell, The University of Texas at Austin; Francesco Topputo, Politecnico di Milano

A systematic approach is devised to find ballistic captures in the planar elliptic restricted three-body problem. Simple periodic orbits around the secondary body of the circular problem, computed through a global grid search, are used as generators for ballistic captures in the elliptic problem. Combining a scaling factor that maps states from the circular to the elliptic case and restricting the motion to emanate from periodic solutions, the search space for ballistic capture is reduced to three dimensions. Results in the Sun-Mars system indicate an abundance of long time-of-flight regular solutions with a variety of characteristics, including low osculating eccentricities.

14:30 **AAS 17-516** **Mapping connections between planar Sun-Earth-Moon libration point orbits**
Zubin Olikara, University of Colorado Boulder; Daniel Scheeres, University of Colorado

Natural connections between L_1 and L_2 libration point orbits in the Sun-Earth and Earth-Moon systems are prevalent. An approach is presented for mapping the full (two-parameter) structure of the main heteroclinic connection families. This study takes into account the phasing of the Sun, Earth, and Moon in a planar, coherent restricted four-body model. System-to-system connections are considered along with heteroclinic transfers including a lunar swingby in the Sun-Earth system. The parameterized families can be used to construct chains of libration point connections following prescribed itineraries.

14:50 **AAS 17-527** **Analytic Approach on Invariant Manifold of Unstable Equilibrium of Restricted （N+1） Body Problem**
Dandan Zheng; Jianjun Luo; Jinglang Feng; RenYong Zhang, Northwestern Polytechnical University; Jianping Yuan

This paper focus on the analytical solutions of invariant manifold of unstable Lagrange equilibrium points of restricted N+1 body problem. Because these equilibrium points exist stable manifolds、 unstable manifolds and center manifolds we can use the improved center manifold theory to obtain Taylor series expansion of neighbourhood of these points, These algebraic equation is independent of time. We obtain the geometric structure of restricted N+1 body problem.The results of three order expansion are consistent with the numerical results. And this approach will avoid explicit numerical differentiation. Restricted three body problem of Earth-moon is studied in detail.

Feb 6, 2017Pavo Real

08 Satellite Constellations

Co Chair: John Seago

13:30 AAS 17-207 MULTIPLE AGILE EARTH OBSERVATION SATELLITES SCHEDULING ALGORITHM ON AREA TARGETS

Xinwei Wang, Beihang University; Yinrui Rao, China Academy of Engineering Physics, Institute of Systems Engineering; Chao Han, Beihang University

Limited to the time windows, it is hard for the ordinary satellite to accomplish the observation mission on the large-scale area target. However, the agile satellite with more attitude freedom could complete the task in a short period. In this paper, a division method is utilized to decompose the area target into several point targets. Then a decomposition optimization algorithm, which consists of a novel multiple satellites assignment method and the graph theory, is adopted to obtain the scheduling results. Furthermore, two typical observing modes are defined according to the practical requirements. Simulations indicate the observation missions have been completed.

13:50 AAS 17-234 Necklace Theory applied to 3-D Lattice Flower Constellations

David Arnas, Centro Universitario de la Defensa - Zaragoza; Daniel Casanova, Centro Universitario de la Defensa; Eva Tresaco, Centro Universitario de la Defensa; Daniele Mortari, Texas A&M University

A new approach in satellite constellation design is presented in this work, based on the 3D Lattice Flower Constellation Theory and introducing the concept of necklace in the theory. This new formulation creates a further generalization of the Flower Constellation Theory, increasing the possibilities of constellation distribution and maintaining the characteristic symmetries of the original theory. Moreover, an example of application is presented, showing the possibilities of this new approach in satellite constellation design.

14:10 AAS 17-217 Constellation Design for Earth Coverage
Andrew Turner, SSL

Orbits for LEO constellations are reviewed and their advantages and disadvantages to assist smallsat operators to reduce system costs are discussed. Economic considerations are paramount so the number of craft must be minimized. Orbits with minimum altitude and inclination reduce launch cost and can optimize observation and communications for specific regions, however requirements to observe other locations, for sun-synchronous orbits, or for rideshare opportunities may dictate higher altitudes and/or higher inclinations. The related trades are discussed. Single-plane, Walker Pattern, Streets of Coverage, Rosette and hybrids of these constellation types are evaluated for coverage of specific regions and the entire Earth.

14:30 AAS 17-360 PERTURBATION IN ORBITAL ELEMENTS OF A HIGH ELLIPTICAL ORBIT OF SATELLITES CONSTELLATION
Osama Mostafa Abdelaziz ALI, Kyushu University; Toshiya Hanada, Kyushu University; Koki Fujita, Kyushu University

With the continual development of astronautical technology, The satellites constellation play an important role in the communication world, Constellation of high elliptical orbit satellites is an important subject of research in the application of small satellites to make a continuous coverage and reduce the station keeping. This work focuses upon the study of the effects of the various perturbations (Oblateness, air drag, solar radiation pressure and solar and lunar gravitation) on the motion of a high elliptical orbit artificial satellite constellation, a computational model developed at the Space Systems Dynamics Laboratory, Kyushu University for these perturbations on the constellation orbit.

14:50 AAS 17-471 Satellite Swarm Localization and Control via Random Finite Set Statistics
Richard Linares, University of Minnesota

This work develops satellite swarming localization and control approaches using Random Finite Sets. It is demonstrating that using Random Finite Sets (RFS) statistics, relatively simple units with limited communication requirements can be employed, providing collective intelligence and expanded capability. The approaches developed for this work are meant for very large swarms, 1000-5000 units, where units are indistinguishable, and there are too many units to represent individual states of each unit. Therefore, the RFS formation models the satellite swarm in a probabilistic way and allows the entire swarm to be parameterized with a probably density function representing both the location and

Feb 7, 2017La Villita A

09 Planetary Missions

Co Chair: Angela Bowes

8:00 **AAS 17-218** **Deep Space Relay to Support Communications between Earth and Mars**
Andrew Turner, SSL

Communications between Earth and the multiple spacecraft in orbit around Mars, and to the landers and rovers on the surface of the planet, are interrupted for approximately a month roughly every two years when the sun lies between the two planets. This paper addresses a means to close this gap by employing a Deep Space Relay (DSR) spacecraft injected into an Earth-trailing orbit and/or the Sun-Earth Lagrange Point L5, which trails Earth in its orbit around the sun. DSR systems issues, enabling technologies and alternative uses are discussed. Maximizing DSR heritage from commercially-produced Earth-orbiting spacecraft is included to control costs.

8:20 **AAS 17-283** **What Goes Up Must Come Down: Cassini Maneuver Experience During the Inclination-Raising Phase Prior to End of Mission**
Frank Laipert, Jet Propulsion Laboratory; Sean Wagner, NASA/JPL; Yungsun Hahn, Jet Propulsion Laboratory; Sonia Hernandez, Jet Propulsion Laboratory; Powtawche Valerino, NASA / Caltech JPL; Mar Vaquero, NASA Jet Propulsion Laboratory; Mau C. Wong, JPL

The Cassini spacecraft is kept on its planned reference trajectory using maneuvers designed by the Cassini Maneuver Team. The experiences of the team are documented for 2016---a span of the mission during which the orbit inclination is steadily increasing. This period contains 33 planned maneuvers and 11 Titan flybys leading up to the final orbits before Cassini's plunge into Saturn. Information about each maneuver is provided along with discussion of situations where operations deviated from the normal routine.

8:40 **AAS 17-287** **Mars Reconnaissance Orbiter: Ten Years of Maneuver Support For Science Operations and Entry, Descent, and Landing Sequences**

Sean Wagner, NASA/JPL; Premkumar Menon, NASA/JPL; Stuart Demcak, Jet Propulsion Laboratory

The Mars Reconnaissance Orbiter (MRO) launched in August 2005 and attained an orbit around Mars in March 2006. After aerobraking and transitioning to its primary science orbit, MRO began science operations in November 2006. Since then, nearly 50 propulsive maneuvers were executed to maintain MRO in its science orbit and position it for relay support of three arriving spacecraft: the Phoenix lander in May 2008, Mars Science Laboratory in August 2012, and the ExoMars Schiaparelli lander in October 2016. This paper will discuss the performance of these maneuvers and MRO's planned support of the InSight Entry, Descent, and Landing in

9:00 AAS 17-308 New Horizons Extended Mission Design to the Kuiper Belt Object 2014 MU69

Yanping Guo, JHUAPL

After the Pluto flyby on July 14, 2015, the trajectory of the New Horizons spacecraft was adjusted through a series of four maneuvers in October-November 2015 to fly by Kuiper Belt Object (KBO) 2014 MU69 on January 1, 2019 for the first time as an extended mission. The KBO flyby will occur at 43.28 AU from the Sun and 44.26 AU from Earth, with a round trip light time of 12.3 hours. The New Horizons extended mission design to the KBO, the post-Pluto trajectory, trajectory adjustment by the initial KBO targeting maneuvers, and the planned KBO flyby trajectories are described.

9:20 AAS 17-337 Mars Reconnaissance Orbiter Navigation Strategy for the ExoMars Schiaparelli EDM Lander Mission

Premkumar Menon, NASA/JPL; Sean Wagner, NASA/JPL; David Jefferson, NASA / Caltech JPL; Eric Graat, NASA/JPL; Kyong Lee, NASA/JPL; William Schulze, NASA/JPL

The Mars Reconnaissance Orbiter (MRO) originally planned to provide primary relay support for the brief surface mission of the ExoMars Schiaparelli EDM Lander on Mars starting on October 19, 2016. Launched with the Trace Gas Orbiter (TGO) in March 2016, Schiaparelli and TGO compose the first part of the ExoMars program. To place MRO directly overhead on its third overflight of the Schiaparelli landing site, two propulsive maneuvers were performed in July and September 2016, respectively. This paper documents the maneuver strategy employed by the MRO Navigation Team to support the Schiaparelli overflight campaign.

9:40 **AAS 17-417** **Recursive Multi-Objective Optimization of Mars-Earth-Venus Trajectories**
Kirk Barrow; Marcus Holzinger, Georgia Institute of Technology

The NASA exploration roadmap envisions a sustainable human presence beyond Earth orbit with an emphasis on Mars habitation. Establishing an interplanetary transportation system in orbits that periodically intersect Earth and Mars have been under study since 1969, but solutions generally suffer from high delta-v requirements, high approach velocities, infeasibly long transit times, or simplifying assumptions like co-planar, circular orbits. This work expands investigations to non-cyclic trajectories that also take advantage of Venusian gravity assists using realistic planetary movement and multi-objective optimization. Results show broad classes of available orbits every calendar year with relatively low required total delta-v (< 8 km/s).

10:00 **Morning Break**

10:20 **AAS 17-437** **ROBUST CAPTURE AND PUMP-DOWN DESIGN FOR THE EUROPA CLIPPER MISSION**
Christopher Scott, The Johns Hopkins University Applied Physics Laboratory; Martin Ozimek, The Johns Hopkins University Applied Physics Laboratory; Brent Buffington, NASA / Caltech JPL; Ralph Roncoli

Missions to the planetary systems of the outer solar system generally contain a system entry sequence. These events potentially involve a propellant reducing flyby, a capture maneuver, and a subsequent set of flybys which reduce energy and set the orbital conditions necessary for a science campaign. This paper addresses the optimality, robustness, and flexibility of a design in the Jovian system with target conditions set by the Europa Clipper Mission. Robustness to spacecraft anomalies is achieved through the orbital design and not through propellant margin. The theoretical limits of the design space are derived before performing a broad trajectory search.

10:40 **AAS 17-457** **Deimos Observation Trajectory Options for Phobos Sample Return Mission**
Kyosuke Tawara, Tokyo Institute of Technology; Yasuhiro Kawakatsu, JAXA / ISAS; Naoko Ogawa, Japan Aerospace Exploration Agency

Japan has been preparing for a Phobos sample return mission. In this mission, it is worth taking the opportunity to also observe Deimos. This paper discusses trajectory options in the case of utilizing a flyby as a Deimos-observation method. There are two problems when designing mission orbits that meet requirements. As a result of mission analysis about various options, it was revealed which mission can be conducted and how much the probe satisfies the requirements. Finally, the effective trajectory to the case that the probe has rendezvous with a satellite of Mars, and flyby with the other satellite is shown.

11:00 AAS 17-522 Interplanetary Trajectories for Ice Giant Missions
Nitin Arora, JPL; Anastassios Petropoulos, NASA / Caltech JPL

Interplanetary Trajectory options for missions to Uranus and Neptune, launching between 2025 and 2037, are presented. Trajectories using Chemical Propulsion, Solar Electric Propulsion and Radioisotope Thermoelectric Generator Electric Propulsion, with up to four planetary flybys are investigated. The effect of different launch vehicles with or without an optimal kick stage, on flight time, inserted mass and propellant throughput, is quantified. To enable simultaneous exploration of both planets, dual-spacecraft trajectories that deliver one spacecraft to each planet from a single launch, are presented. Attractive trajectories and mission opportunities for different multi-element mission architectures are presented.

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10 Trajectory Optimization II

Co Chair: Ryan Russell

8:00 AAS 17-299 Global Search for Low-Energy Transfers to the Moon with Long Transfer Time
Kenta Oshima, Waseda University; Francesco Topputo, Politecnico di Milano; Tomohiro Yanao, Waseda University

The present study globally searches for two-impulse, low-energy transfers to the Moon in the planar bicircular restricted four-body problem with transfer time up to 200 days. A grid search combined with a direct transcription and multiple shooting technique reveals numerous families of optimal low-energy solutions. We investigate characteristics of solutions in terms of two- and three-body parameters, and discuss a trade-off between transfer time and delta-v by exploring Pareto-optimal solutions. Analyzing orbital characteristics based on multi-body dynamics, we show useful perturbations of the Sun, Earth, and Moon to reduce delta-v.

8:20 AAS 17-309 TWO-IMPULSE EVOLUTIONARY OPTIMIZATION OF SATELLITE FORMATION TRAJECTORIES OVER MULTIPLE REVOLUTIONS WITH TOPOLOGICAL CONSTRAINTS

David Hinckley, University of Vermont; Darren Hitt, University of Vermont

In this work we apply the evolutionary algorithm Differential Evolution (DE) to topologically constrained trajectory optimization of a satellite formation limited to two-impulsive maneuvers considering a region of interest that spans multiple revolutions. The motivation and constraints for the problem are drawn from NASA's Magnetospheric Multi-Scale Mission (MMS). A single-revolution framework has been demonstrated to be capable of optimizing trajectories adhering to mission constraints. This two-impulse approach extends the amount of time considered during optimization such that trajectory optimization can be done in a manner that reduces the need for corrective maneuvers.

8:40 AAS 17-410 Using Particle Swarm Optimization for Earth-Return Trajectories from Libration Point Orbits

Mollik Nayyar, Penn State University; David Spencer, Penn State University

This paper presents a methodology to use particle swarm optimization to design optimal space trajectories from Lagrange point orbits to Earth orbits. We present an approximate, computationally inexpensive method to scan the available search space and obtain the locations and trajectories associated the with lowest cost , which can be used as an initial guess that can be used in advanced methods to obtain optimal trajectories. The analysis shows that almost any inclination can be reached from the manifold of a halo Lagrange Point Orbit without incurring huge costs depends on the target location for insertion.

9:00 AAS 17-416 Multi-Tiered Approach to Constellation Maneuver Optimization for Low-Thrust Station-Keeping

Andris Jaunzemis, Georgia Institute of Technology; Christopher Roscoe, Applied Defense Solutions; Marcus Holzinger, Georgia Institute of Technology

This paper presents a multi-tiered approach to constellation-wide optimization of low-thrust station-keeping maneuvers. Starting from the general problem of constellation maneuver optimization, a tractable solution is presented for station-keeping. The approach utilizes a gradient-descent algorithm to efficiently drive each satellite toward its nominal orbit, encapsulating this trajectory optimization in an outer-loop genetic algorithm to optimize within discrete and non-differentiable constellation-level constraints. The output trajectories are validated and refined in a high-fidelity environment using NASA's General Mission Analysis Tool. A concrete example with operational constraints is presented, and limits of the computation-driven assumptions in the tractable solution are assessed.

9:20 AAS 17-429 A Time-Regularized, Multiple Gravity-Assist Low-Thrust, Bounded-Impulse Model for Trajectory Optimization

Donald Ellison, University of Illinois at Urbana-Champaign Aerospace Engineering Department; Jacob Englander, NASA Goddard Space Flight Center; Bruce Conway, University of Illinois at Urbana-Champaign

The multiple gravity-assist low-thrust (MGALT) trajectory model is a computationally efficient preliminary design algorithm, and provides an accurate estimation of the total mass budget that will be required by the flight-suitable integrated trajectory. However, it suffers from one major drawback, namely its temporal spacing of the control nodes. We introduce a variant of the MGALT transcription that utilizes angular anomaly as a decision variable in addition to the propagation time. This results in the maneuver locations occurring at regular angular intervals, and also an iteration-free propagation method. An application problem illustrates the improvements this model has over the MGALT transcription.

9:40 AAS 17-530 Optimal Slew-Rate-Limited Guidance for Combined Formation Establishment and Reconfiguration of Inspector Satellite with Exclusion Cone

Eric Prince, Air Force Institute of Technology; Richard Cobb, Air Force Institute of Technology; Joshuah Hess, Air Force Institute of Technology

GPOPS-II is used to find optimal trajectories for a satellite to inject itself into a natural circumnavigation about a target then optimally transfer to another orthogonal one. Instead of optimizing formation establishment and reconfiguration separately, this work optimizes the combined mission. The trajectories are constrained to avoid an exclusion zone emitting from the target and the control is slew-rate-limited. The thrust is continuous, eliminating the need for pre-defined burn and coast phases. Minimum time and various fixed final time, minimum fuel solutions are calculated. Results show time and fuel savings and provide planners options based on time and fuel requirements.

10:00 Morning Break

10:20 AAS 17-432 Minimum-Time Low Thrust Orbit Transfers using the Method of Particular Solutions

Robyn Woollands, Texas A&M University ; Julie Read, Texas A&M University; John Junkins, Texas A&M University

We have developed a method for solving optimal control minimum time transfers using the method of particular solutions and modified Chebyshev-Picard iteration. The method first computes a sub-optimal solution by iteratively solving for the coefficients of the Chebyshev polynomial that parameterize each of two steering angles of the control vector. This unique implementation of minimum norm direct optimization is attractive in that it does not require partial derivatives, yet we have shown that we can accommodate a relatively high dimensional parameterization of the control variables. Once the sub-optimal solution has been obtained the time-of-flight is reduced incrementally until the method

10:40 AAS 17-439 Low-thrust Trajectory Optimization for Multi-Asteroid Mission: An Indirect Approach

Ehsan Taheri, University of Michigan; Ilya Kolmanovsky, University of Michigan; Anouck Girard, University of Michigan

We investigate the problem of visiting multiple asteroids using low-thrust engines; our solution methodology is based on indirect methods that benefit from two critical components, namely, a smoothing formulation and effective methods for generating initial guesses for the unknown values of the initial costates. Considering transfers between near-circular near-coplanar orbits, two different strategies are considered: 1) to exploit the solution of Lambert's problem, and 2) to simplify the dynamics by ignoring the gravitational parameter of the central body and assuming no fuel consumption. Numerical examples of various low-thrust sequences of asteroids are generated.

11:00 AAS 17-440 Shaping Velocity Coordinates for Generating Low-thrust Trajectories

Ehsan Taheri, University of Michigan; Ilya Kolmanovsky, University of Michigan; Ella Atkins, University of Michigan

This paper investigates application of shape-based methods to spacecraft trajectory optimization. Low-thrust trajectories are represented by the evolution of the velocity coordinates in spherical coordinates and are characterized in terms of an overall required velocity increment ΔV. The defined performance index requires the evaluation of an integral that must be evaluated numerically. This work applies a standard Gauss quadrature scheme shows it is accurate to within 0.1\% of the true index value and substantially faster than trapezoidal integration. The proposed improvements are applied to generate ΔV contours similar to porkchop plots conventionally defined for impulsive maneuvers.

11:20 AAS 17-443 RELATIONSHIPS BETWEEN UNSCENTED AND SENSTIVITY FUNCTION-BASED OPTIMAL CONTROL FOR SPACE FLIGHT

Richard Shaffer, University of California, Santa Cruz; Mark Karpenko, Naval Postgraduate School; Qi Gong, University of California, Santa Cruz

Many space flight problems involve parametric uncertainty in some form which necessitate extra considerations when formulating an optimal control problem. Recently, unscented optimal control, which uses a defined distribution of the parameter to characterize the uncertainty, has been used to mitigate the effects of uncertainty in path planning for unmanned aerial vehicles and in attitude control of satellites. Another approach uses sensitivity functions to define a local, and linear, description of the effects of uncertainty. This paper will explore the relationship between these two optimal control formulations and use an example Zermelo problem to illustrate the comparison.

11:40 AAS 17-445 AUTOMATED GLOBAL OPTIMIZATION OF MULTI-PHASE TRAJECTORIES IN THE THREE-BODY PROBLEM USING A VARIABLE GENE TRANSCRIPTION

Vishwa Shah; Ryne Beeson, University of Illinois at Urbana-Champaign; Victoria Coverstone, University of Illinois at Urbana-Champaign

This paper investigates the use of a variable chromosome transcription to enable construction and global optimization of multi-phase trajectory problems by an automated global optimization framework for multi-body problems. We demonstrate how the variable chromosome transcription operates with NSGA-II, a multi-objective genetic algorithm, to select number of phases and phase types for impulsive and low-thrust missions in three-body transfer problems. For both impulsive and low-thrust transfers, we show how our framework with the variable chromosome transcription naturally converges GA populations to phase-specific groups on multi-objective fronts.

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11 Space Situational Awareness II

Co Chair: Thomas Starchville

8:00 AAS 17-228 An Improved MRP-based Iterative Closest Point-to-Plane Algorithm

Benjamin Bercovici, University of Colorado Boulder; Jay McMahon, University of Colorado

Point-cloud registration pertains to the computation of point pairs between a source and a destination point cloud, followed by the calculation of the rigid transform minimizing a relative distance (such as the Iterative Closest Point-to-Plane distance criterion) between these point pairs. The work described in this paper presents an alternative parametrization of the rotational transform using Modified Rodrigues Parameters. The performance of this formulation is compared to that of Euler angles-based algorithms when the point-pairs are assumed to be known. Results show a better performance for the new MRP formulation in terms of speed and accuracy.

8:20 AAS 17-393 Angles-only Data Association Using Directional Discriminant Analysis

John Kent, University of Leeds; SHAMBO BHATTACHARJEE, University of Leeds; Islam Hussein, Applied Defense Solutions; Moriba Jah, University of Arizona

Suppose that for a library of space objects, their predicted angular positions at the current time are available from previous observations, including an assessment of the errors. Given a new angles-only observation at the current time, the objective is to decide which object, if any, in the libary corresponds to the observed object. The Fisher-Bingham-Kent distribution from directional statistics provides a powerful and tractable model to summarize uncertainty and to implement the classic methods of discriminant analysis from multivariate analysis for this data association problem.

8:40 AAS 17-401 Optical Sensor Follow-up Tasking on High Priority Uncorrelated Track

Timothy Murphy, Georgia Institute of Technology; Kim Luu, AFRL; Chris Sabol, Air Force Maui Optical and Supercomputing; Marcus Holzinger, Georgia Institute of Technology

This work proposes a methodology for tasking of optical sensors to search for an object in a time-optimal manner to enable space situational awareness follow-up on unknown objects. This work looks at follow-up with only the prior knowledge provided by an uncorrelated track (UCT) observed by an arbitrary second optical sensor. Because any follow-up sensor will not be collocated with a space-based sensor in general, and a UCT provides incomplete information, the follow-up region is large. This work provides a method to minimize the time it takes a second ground-based sensor to search through possible locations of the unknown object.

9:00 AAS 17-415 Application of Sequential Monte Carlo Methods for Space Object Tracking

Islam Hussein, Applied Defense Solutions; Waqar Zaidi, Applied Defense; Weston Faber, Texas A&M University; Christopher Roscoe, Applied Defense Solutions; Matthew Wilkins, Applied Defense Solutions; Paul Schumacher, Air Force Research Laboratory; Mark Bolden, Applied Defense Solutions

The problem of producing timely, accurate, and statistically meaningful SSA data products from diverse sources is one of the most challenging class of multi-target tracking problems. The space object tracking problem, in general, is nonlinear in both state dynamics and observations. The general Bayesian filtering problem is often solved using Gaussian mixtures. This paper describes the application of Sequential Monte Carlo for both nonlinear filtering and handling of very large numbers of hypotheses. Since they make no assumptions about the underlying Gaussianity, the proposed multi-object filtering solution provides the most statistically consistent characterization of uncertainty for Bayesian filtering.

9:20 AAS 17-477 **Multiple Space Object Tracking using Randomized Finite Set Statistics (R-FISST)**

Weston Faber, Texas A&M University; Suman Chakravorty; Islam Hussein, Applied Defense Solutions

Randomized Finite Set Statistics (R-FISST) is a technique that has been developed to keep the multi-object tracking problem computationally tractable. It does this by using a Markov Chain Monte Carlo (MCMC) random sampling technique that solves the Data Association Problem (DAP) inherent to multi-object tracking problems in a computationally tractable fashion. This is true for cases that include clutter, multiple birth, and multiple death. In previous literature, the technique has been demonstrated using simplified two-dimensional Space Situational Awareness (SSA) examples. This paper will show the application of the R-FISST methodology to real SSA scenarios using the public Two Line Elements.

9:40 AAS 17-517 **A SUMMARY OF EMERGING RESEARCH IN THE NEW BIG DATA SPACE SITUATIONAL AWARENESS PARADIGM**

Douglas Hendrix, ExoAnalytic Solutions; Michael Bantel, ExoAnalytic Solutions; William Therien, ExoAnalytic Solutions; Brien Flewelling, ExoAnalytic Solutions; Ben Lane, ExoAnalytic Solutions; Phillip Cunio, ExoAnalytic Solutions; Mark Jeffries, ExoAnalytic Solutions

Orbit determination, behavioral analysis, space object characterization, and other fundamental problems underpinning the Space Situational Awareness (SSA) mission need not be based on inferring information from sparse data collections. With the emergence of commercial networks with orders of magnitude more data sources observing space objects than have been available before new problems are emerging of great interest to the community. Their solutions will provide important capabilities which will enable a better understanding of the behavior of objects in space. We summarize here three such problems enabled by data collected by global networks.

10:00 **Morning Break**

Feb 7, 2017Pavo Real

12 Dynamics and Control of Large Space Structures and Tethers

Co Chair: Maruthi Akella

8:00 **AAS 17-201** **Observer/Kalman Filter Identification (OKID) by a Kalman Filter of a Kalman Filter**

Minh Phan, Dartmouth College; Francesco Vicario, Philips Research North America; Richard Longman, Columbia University; Raimondo Betti, Columbia University

A recent version of Observer/Kalman filter Identifictaion (OKID) uses an estimated Kalman filter residual to convert a stochastic system identification problem into a deterministic one, then identifies a state-space model and its associated steady-state Kalman filter gain from a set of input-output data. Since the estimation of the Kalman filter residual itself is not exact, a second Kalman filter can be employed to model the error in the estimated residual of the first Kalman filter. This paper describes a method where both a system state-space model and the first and second Kalman filter gains are identified directly, optimally, and simultaneously.

8:20 **AAS 17-205** **Converting a State-Space Model to Physical Coordinates Without A Full Set of Sensors: A Kronecker-Based Method**

Dong-Huei Tseng; Minh Phan, Dartmouth College; Richard Longman, Columbia University

This paper presents a method to convert an identified state-space model of a structure to physical coordinates. Once in physical coordinates, methods are available to recover the structure mass, stiffness, and damping matrices. The new development removes the restriction of a recently developed method that requires a full set of sensors, one per degree of freedom. Sensors can now be exchanged for actuators, and one collocated pair of sensor and actuator is required.

8:40 **AAS 17-387** **Tether-Nets for Active Space Debris Removal: Effect of the Tether on Deployment and Capture Dynamics**

Eleonora Botta, McGill University; Inna Sharf, Mcgill University; Arun Misra, McGill University

A promising method to mitigate the space debris problem is to actively capture and remove debris by means of tether-nets. The chaser-tether-net-debris system is modeled with rigid bodies connected by constraints; the tether can be spooled in and out by controlling a winch on the chaser. Through dynamics simulation, this paper analyses the effect of the tether and its tensioning on net deployment and capture dynamics of space debris. This provides interesting insight into the preferred winching of the tether and into the feasibility of using the tether as a closing mechanism.

9:00 AAS 17-301 A NOVEL VIBRATION DAMPER FOR SMALL SPACECRAFT WITH LARGE FLEXIBLE APPENDAGES

Robert Waelchli, Embry-Riddle Aeronautical University; Dongeun Seo, Embry-Riddle Aeronautical University

This paper talks about the structural vibration control of the relatively large appendage to the satellite. A novel vibration damper is proposed based on the viscoelastic properties of the magnetorheological (MR) fluid. MR fluid can change its viscosity and yielding stress with respect to the applied external magnetic field. Numerical simulations are performed to demonstrate the viability of the proposed actuator design. In simulations, the MR fluid stripe is proposed as an active damper to dampen out the vibration induced by the solar panels.

9:20 AAS 17-345 DYNAMIC ANALYSIS OF THE TETHER TRANSPORT SYSTEM USING ABSOLUTE NODAL COORDINATE FORMULATION

Xin Sun; Rui Zhong; Shijie Xu

This paper studies the dynamics modeling of a tether transport system, which consists of two spatial bodies connected by an elastic tether with mass transfer chambers, and performs the dynamic modeling of the tether transport system employing the absolute nodal coordinate formulation. Comparisons between the current results and the existed lumped mass tether model are carried out through numerical simulation on accuracy and computational efficiency.

9:40 AAS 17-455 SATLEASH - PARABOLIC FLIGHT VALIDATION OF TETHERED-TUGS DYNAMICS AND CONTROL FOR RELIABLE SPACE TRANSPORTATION APPLICATIONS

Vincenzo Pesce; Andrea Bellanca, Politecnico di Milano; Michèle Lavagna, Politecnico di Milano; Paolo Lunghi, Politecnico di Milano; Riccardo Benvenuto, Politecnico di Milano - DAER; Simone Flavio Rafano Carnà, Politecnico di Milano

The SatLeash experiment investigates the dynamics and control of tow-tethers, for space transportation, being an appealing concept for Active Debris Removal missions. A wavebased control, using tension feedback, is selected as effective method to stabilize the system during tensioning and release phases. The team exploits a multibody dynamics simulator – developed at PoliMi-DAER - to describe tethered-satellite-systems dynamics and synthetize their control. This is considered of primary importance to design future missions. The experiment, selected to fly in microgravity conditions by the ESA FlyYourThesis! 2016 programme, focuses on validating the adopted models and verifying the implemented control law.

10:00 **Morning Break**

10:20 **AAS 17-494** **DYNAMIC SUBSTRUCTURING BASED DECENTRALIZED CONTROL FOR LARGE SPACE STRUCTURES**

Quan Hu; Yinguo CAO, Beijing Institute of Technology ; Jingrui Zhang

A decentralized control strategy is proposed for the attitude stabilization and vibration suppression of large space structures (LSS) with distributed actuators and sensors. The LSS is viewed as a set of connected substructures. Constraint forces and torques, and control input exist at the connection. The equations of motion of the LSS are written by the dynamic substructuring method. For each substructure, an output feedback control law only requiring the information of the local sensors is designed. The stability of the overall system are proved by the extraction and contraction of the subsystems.

10:40 **AAS 17-505** **gravitational force and torque of a solar power satellite considering the structure flexibility**

Yi Zhao; Quan HU; Jingrui Zhang

The solar power satellites (SPS) are designed to collect the constant solar energy and beam it to Earth. They are traditionally large in scale and flexible in structure. In order to obtain an accurate model of such system, the analytical expressions of the gravitational force and gradient torque are investigated. They are expanded to the fourth order in a Taylor series with the elastic displacements considered. It is assumed that the deformation of the structure is relatively small compared with its characteristic length, so that the assumed modes method is applicable. The high-order inertia and flexibility coefficients are presented. Numerical

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13 Asteroid Missions II

Co Chair: Nathan Strange

13:30 AAS 17-260 Hydrazine Conservation for the Dawn Spacecraft Operations at the Dwarf Planet Ceres

Ryan Lim, NASA Jet Propulsion Laboratory

After successfully completing its prime Vesta and Ceres missions, Dawn is now in its extended mission, continuously exploring Ceres. After losing the second reaction wheel assembly during departure from Vesta, the feasibility of the Ceres mission was at risk due to the potentially significant increase in hydrazine consumption from using only the reaction control system thrusters. This paper summarizes the intense, collaborative efforts undertaken by the Dawn's project to conserve hydrazine. A special emphasis is given to describing various efforts taken by the Attitude Control Subsystems team. Various simulation results are presented and compared against actual flight data obtained.

13:50 AAS 17-270 Hybrid Guidance Control for a Hypervelocity Small Size Asteroid Interceptor Vehicle

Melak Zebenay, NASA- Goddard Space Flight Center; Joshua Lyzhoft; Brent Barbee, NASA Goddard Space Flight Center

This paper focuses on the development of hybrid guidance navigation and control (GNC) algorithms for precision hypervelocity intercept of small size Near-Earth Objects (NEOs). The spacecraft's hypervelocity and the NEO's small size are critical challenges for a successful mission as the NEO will not fill the field of view until a few seconds before intercept. The investigation needs to consider the error sources modeled in the navigation simulation such as spacecraft inital state uncertainties in position and velocity, 3-axis spacecraft attitude, and random centroid pixel noise with bias.

14:10 AAS 17-284 Dynamics and Modeling of a Binary Asteroid System with Applications to 65803 Didymos

Alex Davis, University of Colorado, Boulder; Daniel Scheeres, University of Colorado

We apply a new methodology for computing the dynamics of the Full Two-Body Problem to investigate the dynamics and equilibria of a binary asteroid system. The goal of this study is to understand the comparative effects of higher order shape model expansion levels on the behavior of a binary asteroid system and to apply these higher order shape models to equilibria computations of binary systems. For our model we use the detailed binary asteroid model 1998KW4 scaled to the 65803 Didymos system, in order to help predict expected behaviors for the AIDA mission which will explore this system in 2020.

14:30 AAS 17-305 Search for Stable Regions in the Irregular Haumea-Namaka Binary System

Diogo Sanchez, National Institute for Space Research - INPE; Kathleen Howell, Purdue University; Antonio Fernando Bertachini Prado, INPE

This work aims to describe the dynamics of small spacecraft around a binary system comprised by irregular bodies Haumea and Namaka. In this model, the dynamics of Haumea and Namaka is assumed as a full two body problem, considering the inclination of Namaka, and the equations of motion of the spacecraft are written incorporating the information from this model, also considering the eccentricity of Namaka's orbit. We found interest regions in the system, formed by periodic and quasi-periodic orbits, where the integral of the acceleration technique can be applied to find the delta-V required to create delta-V assisted periodic orbits.

14:50 AAS 17-306 Applications of refined Lagrangian coherent structures to capture Near-Earth Asteroids in nonautonomous multi-body problem

Xiaoyu Wu, Beijing Institute of Technology ; Haibin Shang, Beijing Institute of Technology ; Xiao Qin, Beijing Institute of Technology

This paper discusses the applications of refined Lagrangian coherent structures to capture Near-Earth Asteroids in nonautonomous multi-body system. The capture trajectory is constructed by two segments, that transfers to Sun-Earth L2 substitution and transfers to Earth-Moon L2 substitution. A method is developed utilizing FTLE that exerting a small velocity increment to the target. Several transport barriers are identified using refined Lagrange coherent structures when the asteroid transfers to the Moon. The results reveal the capture mechanism and indicate that it is feasible for an asteroid to be captured by the Moon.

15:10 AAS 17-315 Sensitivity Analysis of Surface Feature Navigation Using Stereophotoclinometry

Andrew Liounis, NASA Goddard Space Flight Center; Coralie Jackman, KinetX Aerospace; Kenneth Getzandanner; Leilah McCarthy, KinetX, Inc.

Missions that plan to orbit and navigate about small bodies frequently need to rely on optical navigation (OpNav) in order to generate relative state information between the spacecraft and the target. The current state of the art for OpNav in close proximity to a small body is the process of Stereophotoclinometry (SPC), which uses images to generate a

three-dimensional model of the body, and then uses the produced model to navigate about the body. This paper performs sensitivity analysis on the navigation portion of SPC through the use of Monte Carlo analyses with synthetic images of the asteroid Bennu.

15:30 **Afternoon Break**

15:50 **AAS 17-326** **The Dynamics of Comet Shoemaker-Levy 9: Initial Capture Phase**
Travis Swenson, Stanford University; Robyn Woollands, Texas A&M University ; Martin Lo, JPL

The impact of Comet Shoemaker-Levy 9 (SL9) with Jupiter in 1994 was the ultimate confirmation of Eugene Shoemaker's theory that impacts are a common, fundamental process in the Solar System. We tend to visualize these collisions as billiard balls hitting one another. But how, exactly, do they occur? In this paper we investigate the effects of Lyapunov orbits, halo orbits, and their associated invariant manifolds, on the orbital motion motion of SL9. We demonstrate that periodic orbits act as gateways to Jupiter, and their invariant manifolds control the dynamics of SL9 during the Initial Capture Phase.

16:10 **AAS 17-346** **AN ANALYSIS OF LOW-THRUST ORBITAL MANEUVERS AROUND SMALL BODIES**
Don Kuettel, Colorado Center for Astrodynamics Research; Jay McMahon, University of Colorado

This paper examines the feasibility of using low-thrust propulsion for maneuvering around small bodies such as asteroids and comets. Due to the low gravity around small bodies, spacecraft in orbit are able to perform complicated orbital maneuvers with little thrust. Current small body missions (e.g. OSIRIS-Rex and Rosetta) use chemical thrusters which are inefficient for maneuvering in this low gravity environment. It is hypothesized that low-thrust propulsion may be used to more efficiently maneuver spacecraft in this environment. This paper studies the orbital characteristics and maneuver costs of small bodies using asteroid 101955 Bennu as a test environment.

16:30 **AAS 17-422** **SMALL-BODY SPIN-STATE DETERMINATION USING LANDED-TRANSPONDERS**
Andrew French; Jay McMahon, University of Colorado

A new method for small-body spin-state estimation is presented here. This paper investigates the effectiveness of using landed radiometric transponders to estimate torque-free rigid body dynamics. Solution accuracy is quantified in terms of measurement quality to determine if landed transponders can be used to improve upon current methods, such as ground based radar and satellite based optical tracking. Accurate spin-state characterization of asteroids and comets is vitally important to both mission navigators and scientists as the rotation rate and pole orientation can be used to place constraints on internal density distributions and provide insights into rotational evolution and history.

16:50 AAS 17-444 Comparing the Computational Efficiency of Polyhedral and Mascon Gravity Models

Jason Pearl, University of Vermont; Darren Hitt, University of Vermont

The polyhedral potential model determines the gravitational potential using a polygonal mesh that approximates the surface topology of an asteroid. As a results few computational elements are needed, however, the methods is computational intensive on a per element basis. The mascon model, on the other hand, is simple but requires the volume to be discretized, and thus a large number of computational elements. In the present study, the computational efficiency (i.e. accuracy per unit run-time) of these two methods is compared. Results indicate that the mascon model can produce more accurate results than the polyhedral model with a shorter run-time.

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14 Orbital Dynamics I

Co Chair: Roby Wilson

13:30 AAS 17-222 Orbit Propagation Theory using Kustaanheimo-Stiefel Regular Elements with Luni-solar Gravity, Oblateness, and Atmospheric Drag Perturbations

Harishkumar Sellamuthu, Karunya University; Ram Krishan Sharma, Karunya University

A non-singular analytical solution for orbit propagation in terms of Kustaanheimo-Stiefel regular elements with respect to luni-solar gravity, oblateness, and atmospheric drag perturbations is developed. Accurate positions of the Sun and the Moon are computed using Plataforma Solar de Almería (PSA) algorithm and a Fourier series algorithm, respectively. An oblate diurnally varying atmospheric model for atmospheric drag and Earth's zonal harmonic terms (J2 to J4) for non-sphericity effects are considered. Comparisons between computed and observed values of the orbital parameters for few test cases are carried out and the results are found to be satisfactory.

13:50 **AAS 17-251** **On the Formation and Stability of Resonant Planetary Systems**
Flavien Hardy; Gong Shengping

This study aims at generalizing the existing analytical conditions for asymptotically unstable dynamics to the general three-body problem in the vicinity of a mean-motion resonance. In the context of a dissipative migratory scenario, a system with overstable librations might still be trapped into a stable resonant state under particular evolutionary conditions; this might offer some insights on the evolutionary scenarios that could have led to the formation of multi-planetary systems with few resonant pairs.

14:10 **AAS 17-261** **Dynamics of libration points in the general asynchronous binary asteroid system**
Xiaosheng Xin, Nanjing University; Xiyun Hou; Lin Liu, Nanjing University; Jinglang Feng

The dynamical substitutes of the libration points of the asynchronous binary asteroid system are studied. Equations of motion truncated at 2nd order of the non-spherical terms are derived for the massless body in the binary system of two ellipsoids that revolves around each other under their mutual potential also truncated at 2nd order. External perturbations with two frequencies due to the non-spherical terms of the primaries in near-circular orbit contribute to the motion of the massless body. Therefore, the libration points become quasi-periodic orbits. We obtain the corresponding quasi-periodic orbits, analyze their stability properties and verify our results with numerical simulations.

14:30 **AAS 17-262** **Dynamics of the 1:1 spin-orbit resonance around uniformly rotating asteroids ---the approach of periodic orbits**
Jinglang Feng; Xiyun Hou; Xiaosheng Xin, Nanjing University

This study addresses the dynamics of 1:1 spin-orbit resonance between the rotation of the asteroid and the orbital motion of the spacecraft or particles, by exploring the genealogy and stability of periodic families around equilibrium points (EPs) in the body-fixed frame of the asteroid. By studying the stability of these periodic families, the following questions can be answered such as: what is the largest eccentricity within which the near-equatorial orbits can stay stable; how the orbital stability evolves with respect to the orbital inclination.

14:50 **AAS 17-266** **EFFICIENT UNCERTAINTY PROPAGATION OF PERTURBED SATELLITE MOTION**
Ahmad Bani Younes, Khalifa University, Abu Dhabi; Mohammad Alhulayil, Khalifa

University; James Turner, Texas A&M University

Modeling and simulation for complex applications in science and engineering develop behavior predictions based on mechanical loads. We propose an efficient method to propagate perturbed motion uncertainity using differential computation tools. Several applications, using nonlinear systems, are presented that demonstrate the effectiveness of the proposed mathematical developments, where the solution is validated by using a Mont-Carlo simulation method. The perturbed two-body problem, where the earth gravity potential is the spherical harmonic Earth gravitational model, is studied.

15:10 AAS 17-269 Orbit Maintenance and Navigation of Human Spacecraft at Cislunar Near Rectilinear Halo Orbits (NRHO)

Diane Davis, a.i. solutions, Inc.; Sagar Bhatt; Kathleen Howell, Purdue University; Jiann-Woei Jang; Ryan Whitley, NASA; Fred Clark; Davide Guzetti; Emily Zimovan, Purdue Univeristy; Gregg Barton, Draper

Multiple studies have indicated that Earth-moon libration point orbits are attractive candidates for staging operations. The Near Rectilinear Halo Orbit (NRHO), a type of Earth-moon halo orbit, has been demonstrated to meet multi-mission architectural constraints. In this paper, the operational challenges associated with operating human spacecraft in the NRHO are evaluated. Navigation accuracies and human vehicle process noise effects are applied to various stationkeeping strategies in order to obtain a reliable orbit maintenance algorithm. Additionally, the ability to absorb missed burns, construct phasing maneuvers to avoid eclipses and conduct rendezvous and proximity operations are examined.

15:30 Afternoon Break

15:50 AAS 17-278 Osculating Keplerian Elements for Highly Non-Keplerian Orbits

Alessandro Peloni, University of Glasgow; Colin McInnes, University of Glasgow; Matteo Ceriotti

This paper presents a mapping between highly non-Keplerian orbits properties and classical orbital elements. Three sets of elements are discussed and mappings are derived in closed, analytical form for both the direct and inverse problem. Advantages and drawbacks of the use of each set of elements are discussed. A sensitivity analysis is performed on all mappings presented. The spacecraft thrust-induced acceleration used to generate families of non-Keplerian orbits is extracted from the inverse mapping from the osculating orbital elements. The key signatures of non-Keplerian orbits in Keplerian elements tracking data are determined through a set of test cases.

16:10 AAS 17-282 Semi-Analytical Propagation With Drag Computation and Flow Expansion Using Differential Algebra

David Gondelach, University of Southampton; Roberto Armellin, Universidad de La Rioja; Hugh Lewis, University of Southampton; Juan Félix San-Juan, University of La Rioja; Alexander Wittig, Politecnico di Milano

Space situational awareness requires efficient methods for long-term propagation. A technique that combines accuracy and efficiency is semi-analytical propagation. However, the modelling of non-conservative forces in semi-analytical methods limits their efficiency, because accurate calculation of their effects requires numerical quadrature. In this work we apply DA for efficient evaluation of the mean element rates due to drag. Furthermore, the semi-analytical propagator is entirely implemented in DA to enable higher-order expansion of the flow that can be used for efficient propagation of initial conditions. The methods are tested for decaying LEO and HEO orbits and a Galileo disposal orbit.

16:30 AAS 17-294 Revision of the Lie-Deprit Method in General Perturbations Theories of Astrodynamics Problems

Juan Félix San-Juan, University of La Rioja; Iván Pérez, University of La Rioja; Montserrat San-Martín, University of La Rioja; Rosario Lopez

An extension of the classical Delaunay normalization is analyzed. It takes advantage of the intrinsic arbitrariness of the Lie-Deprit method in the process of calculating its generating function. We have found that, under certain conditions, a function belonging to the null space of the Lie operator associated to the unperturbed part of the initial Hamiltonian, can be added to the generating function at each order, so that the long-period terms can be removed from the transformation equations, or to eliminate several angles simultaneously in the cases of the Artificial satellite problem, Lunar theory and Planetary satellites.

16:50 AAS 17-320 Rapid Charged Geosynchronous Debris Perturbation Modeling of Electromagnetic Disturbances

Joseph Hughes; Hanspeter Schaub, University of Colorado

Electrically charged space objects experience electrostatic torques and forces being produced due to the interactions with the local electric and magnetic fields. For objects with high charge to mass ratios, these charging related disturbances are shown to become significant for particular space weather conditions. This paper investigates faster-than-realtime numerical methods, such as Appropriate Fidelity Measures and the Multi-Sphere Method, to approximate these perturbations on a range of uncontrolled space debris objects. A range of dynamics scenarios are discussed to illustrate when the charging perturbations, the SRP force, Eddy currents, or combinations thereof drive the orbit motions departures.

17:10 AAS 17-338 Impact of Special Perturbations on LAGEOS1, AJISAI, LARES and STELLA's orbit prediction accuracy

Claire Gilbert, Integrity Applications Incorporated - PDS; Channing Chow, Pacific Defense Solutions; Steven Long, Integrity Applications Incorporated - PDS; Jack Wetterer, Integrity Applications Incorporated

Precise orbit estimation and propagation require a sophisticated dynamic model to accurately predict the spacecraft's trajectory. This paper examines how various combinations of perturbations in the equation of motion impact the orbit propagation accuracy of LAGEOS1, AJISAI and STELLA over two months . LAGEOS1's orbit could be modeled with less than 5 m RMS position error over the whole two months propagation span, compared with 28 days for AJISAI and a couple days only for STELLA. The type of atmospheric model selected was found to impact AJISAI's orbit the most and extended time for which the satellite's position was predicted accurately by about 20 days.

17:30 AAS 17-369 Migration of the DSST Standalone to C/C++

Juan Félix San-Juan, University of La Rioja; Rosario Lopez, Center for Biomedical Research of La Rioja, CIBIR; Ricardo Suanes, University of La Rioja; Iván Pérez, University of La Rioja; Paul Cefola, University at Buffalo, State University of New York; Srinivas Setty, DLR/GSOC

The Draper Semi-analytical Satellite Theory (DSST) Standalone orbit propagator combines the speed of analytical propagators with the accuracy of numerical propagators. DSST exhibits linear behavior, ease of estimation, and longer uncertainty handling. DSST is publicly available in its original Fortran 77 form and in the Orekit Java library. The current project migrates the original Fortran 77 DSST code to C/C++. The original design will be maintained as much as possible, to facilitate use of existing test resources. Then, different parallelization strategies will be considered. Finally, complexities associated with application to orbits with arbitrary central bodies will be addressed.

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15 Orbit Determination and Space-Surveillance Tracking

Co Chair: Moriba Jah

13:30 AAS 17-215 In-Orbit Tracking of High Area-to-Mass Ratio Space Objects
Daniel Brack, University of Colorado; Pini Gurfil, Technion – Israel Institute of Technology

High area-to-mass ratio objects at geosynchronous orbits pose a threat to operational satellites. This paper develops an in-orbit on-board algorithm for tracking high area-to-mass ratio space objects. The design utilizes relative motion dynamics and a simplified stereo-camera measurement model for tracking the object's position, velocity, and solar radiation pressure coefficient. The simulation results show that the tracking algorithm estimates the tracked object position, velocity, and solar radiation pressure coefficient in different scenarios with high accuracy. The simulations show that although shape information is lost in the measurement model, the solar radiation pressure coefficient can still be estimated.

13:50 AAS 17-310 Correlation of observations and orbit recovery considering maneuvers
Jan Siminski, ESA/ESOC; Hauke Fiedler, German Aerospace Center (DLR); Tim Flohrer, European Space Agency

Optical tracklets collected after or during a maneuver phase cannot be directly associated to any cataloged object. The observations do not provide enough information for an independent orbit determination. Thus, the new orbit remains uncertain before collecting any additional measurements. Two methods for the correlation and orbit recovery are presented. First, the solution space after the maneuver is bounded using an admissible region. Second, the historic maneuver data of each object is characterized to compute the association likelihood and predict the most likely state after a maneuver. The performance of the presented approaches is demonstrated using data of Eumetsat satellites.

14:10 AAS 17-327 Relative-Motion Approach for Di fferential Correction in Orbit Determination
Andrew Sinclair, Auburn University; Alan Lovell; Kenneth Horneman, Barron Associates Inc.; Andrew Harris, SUNY Buffalo; Alex Sizemore, University of Kansas

This paper describes an approach for differential correction for angles-only orbit determination based on relative motion. Relative-orbit determination has traditionally been formulated for a space-based sensor in close proximity to the observed object. However, these approaches can be generalized for a distant sensor, and the motion of the observed object is described relative to some proximate reference orbit. The relative-orbit solution is used to define a new reference orbit in the next iteration, reducing approximation error in the relative-motion dynamics. The presented approach utilizes available analytic relative-motion solutions and does not introduce any linearizing approximation in the measurements.

14:30 AAS 17-374 A new multi-target tracking algorithm for a large number of orbiting objects

Emmanuel Delande, Heriot Watt University, School of Engineering & Physical Sciences; Jeremie Houssineau, Heriot Watt University, School of Engineering & Physical Sciences; Jose Franco; Carolin Frueh, Purdue University; Daniel Clark, Heriot Watt University, School of Engineering & Physical Sciences

This paper demonstrates the applicability of the filter for Hypothesised and Independent Stochastic Populations (HISP), a multi-target joint detection/tracking algorithm derived from a recent estimation framework for stochastic populations, to wide area surveillance scenarios in the context of Space Situational Awareness. Designed for multi-object estimation problems where the data association between targets and collected observation is moderately ambiguous, the HISP filter has a linear complexity with the number of maintained tracks and the number of collected observations, and is a scalable filtering solution adapted to large-scale target tracking scenarios.

14:50 AAS 17-382 Dempster-Shafer Theory Applied to Admissible Regions

Johnny Worthy, Georgia Institute of Technology; Marcus Holzinger, Georgia Institute of Technology

The admissible region approach is often used a bootstrap method to initialize a Bayesian state estimation scheme for too-short-arc measurements. However, there are ambiguities in how prior probabilities are assigned for states in the admissible region. The application of Dempster-Shafer evidential reasoning theory to the admissible region problem can avoid these ambiguities by eliminating the need to make any assumptions on the prior probabilities. Dempster-Shafer theory also enables testing of the validity of the assumptions used to construct the admissible region. This paper formulates the admissible region in terms of Dempster-Shafer theory and applies it to state estimation from admissible regions.

15:10 AAS 17-412 Nonlinear Gaussian Mixture Smoothing for Orbit Determination

Kyle DeMars, Missouri University of Science and Technology

The forward filtering solution to the Bayesian estimation problem provides the best possible solution for a probability density function given all past and current data. The backward smoothing solution, by contrast, makes use of all data over an interval in order to determine an improved solution for the probability density function. Achieving a better understanding of the probabilistic description of the state in orbit determination is key to providing reliable situational awareness. This paper investigates a method of combining forward filtering and backward smoothing solutions for non-Gaussian distributions in the orbit determination problem.

15:30 **Afternoon Break**

15:50 **AAS 17-413** **Practical Demonstration of Track-to-Track Data Association Using the Bhattacharyya Divergence**

Christopher Roscoe, Applied Defense Solutions; Islam Hussein, Applied Defense Solutions; Joseph Gerber, Applied Defense Solutions; Jason Stauch, Applied Defense Solutions; Thomas Kelecy, Applied Defense Solutions; Matthew Wilkins, Applied Defense Solutions; Mark Bolden, Applied Defense Solutions; Paul Schumacher, Air Force Research Laboratory

Building and maintaining a space object catalog requires rigorous methods for data association in order to maintain consistent object custody. There are three primary types of data association of interest in space surveillance: observation-to-track association, track-to-track association (TTTA), and observation-to-observation association. Recent work has suggested the use of information-theoretic quantities as metrics for data association. This work presents a demonstration of using one of these, the Bhattacharyya divergence, for TTTA in a GEO catalog maintenance exercise fed by data from a consortium of commercial electro-optical sensors. The Constrained Admissible Region-Multiple Hypothesis Filter is used for orbit determination and track maintenance.

16:10 **AAS 17-448** **On the Equivalence of FISST and MHT for Multi-Target Tracking**

Suman Chakravorty; Weston Faber, Texas A&M University; Islam Hussein, Applied Defense Solutions

In this paper, we propose a hypothesis dependent derivation of the FISST equations that shows that the FISST probability density function (pdf) has a hypothesis dependent structure identical to the Multi-Hypothesis Tracking (MHT) method for multi-target tracking. The only significant difference between the two methodologies stems from the manner in which target birth and death are handled in the two methods. Furthermore, the derivation implies that the most critical element in any MTT technique is the computationally tractable handling of the large number of hypotheses that may result from the ambiguities inherent in the problem.

16:30 AAS 17-449 Computer Vision and Computation Intelligence for Real-time Multi-Modal Space Domain

Mark Bolden, Applied Defense Solutions; Paul Schumacher, Air Force Research Laboratory; David Spencer, Penn State University; Islam Hussein, Applied Defense Solutions; Matthew Wilkins, Applied Defense Solutions; Christopher Roscoe, Applied Defense Solutions

This paper presents a computer vision and computational intelligence approach to space domain awareness. The approach is specifically designed to produce probabilistic density functions and state estimates in real-time for objects within the domain. PDFs are also generated for regions where there are no objects, and where there is insuffient information to assert object existence. The approach is dynamic and naturally adapts to changes of state to include maneuvering objects. The processing speed of the approach is independent of the number of objects, instead only dependent on the size of the domain, the accuracy desired in all dimensions, and the computational architecture.

16:50 AAS 17-452 Initial Orbit Identification: Comparison of Admissible Region Mapping for Too Short Arc Observations

Fouad Khoury, Purdue University; Carolin Frueh, Purdue University

This paper investigates the orbit identification problem and proposes a novel method for correlating two sets of angle-angle rate line-of-sight (LOS) measurements taken at different times by a topocentric observer. Using the concept of the admissible region, a region of attributable space can be computed from an observation at t1 to incorporate all possible sets of range and range-rate values that, combined with angle measurements, satisfy the zero-energy condition set by employing the two-body energy equation. Points from this region are then propagated to a certain time to generate a momentum map used to correlate the orbit with another observation at t2.

Feb 7, 2017Pavo Real

16 Attitude Dynamics and Control I

Co Chair: Roberto Furfaro

13:30 AAS FINITE-TIME ATTITUDE TRACKING CONTROL FOR SPACECRAFT

17-211 WITHOUT ANGULAR VELOCITY MEASUREMENT

Boyan Jiang, Harbin Institute of Technology; Chuanjiang Li; Yanning Guo, Harbin Institute of Technology; Hongyang Dong

This paper investigates the finite-time output feedback problem of attitude tracking control for spacecraft. It is assumed that the angular velocity information is not available for the controller design. An adding a power integrator technique based filter is designed to generate the pseudo-angular-velocity estimates, then a finite-time output feedback attitude tracking controller is developed with relative-attitude-only measurement. Overall finite-time stability of the entire closed-loop system is given, which shows the attitude tracking errors will converge into a region of zero in the presence of external disturbance.

13:50 AAS 17-225 Attitude Quaternion Estimation Using a Spectral Perturbation Approach

Adam Bruce, Raytheon Missile Systems

All quaternion methods for static attitude determination currently rely on either the spectral decomposition of a 4 x 4 matrix (q-Method) or finding the maximum eigenvalue of a 4th-order characteristic equation (QUEST). Using a spectral perturbation approach, we show it is possible to analytically estimate the attitude quaternion to high accuracy and recursively calculate the maximum-likelihood attitude quaternion to arbitrary numerical precision. Analytic or recursive estimation removes several numerical difficulties which are inherent to state-of-the-art algorithms, suggesting our results may substantially benefit high frequency and limited memory embedded software implementations, such as those commonly used on spacecraft computers.

14:10 AAS 17-249 SPIN PARAMETERS AND NONLINEAR KALMAN FILTERING FOR SPINNING SPACECRAFT ATTITUDE ESTIMATION

Halil Ersin Soken, Japan Aerospace Exploration Agency; Sakai Shin-ichiro, Japan Aerospace Exploration Agency ; Kazushi Asamura, Japan Aerospace Exploration Agency; Yosuke Nakamura, Japan Aerospace Exploration Agency; Takeshi Takashima, Japan Aerospace Exploration Agency

In this study, we propose to parameterize the attitude of a spin spacecraft using a set of spin parameters. These parameters consist of the spin axis orientation unit vector in the inertial frame and the spin phase angle. The attitude matrix and the kinematics equations are derived in terms of spin parameters. An Unscented Kalman Filter (UKF) is used to estimate the attitude of the spacecraft in these parameters. The estimation results are compared with those of a quaternion based UKF in different scenarios using the simulated data for the ERG spacecraft of JAXA.

14:30 **AAS 17-250** **SPIN-AXIS TILT ESTIMATION ALGORITHM WITH VALIDATION BY REAL DATA**

Halil Ersin Soken, Japan Aerospace Exploration Agency; Jozef van der Ha, Consultant; Sakai Shin-ichiro, Japan Aerospace Exploration Agency

This paper evaluates a simple spin-axis tilt (SAT) estimation algorithm by means of real in-flight data. The algorithm is based on the Singular Value Decomposition (SVD) and makes use of the attitude rates estimated by an attitude filter. The accuracy of the algorithm is investigated using the data gathered over different orbits. The results are compared with a straightforward averaging method for the SAT determination. The SVD-based SAT estimation algorithm (SVD-SAT) provides robust estimation results without being highly affected by sensor biases. This is in contrast with the averaging method, which is more sensitive to other errors.

14:50 **AAS 17-255** **The Theory of Connections. Part 1: Connecting Points**

Daniele Mortari, Texas A&M University

This study introduces a procedure to obtain general expressions, y = f(x), subject to constraints on the function and its derivatives specified at specific values. These \emph{constrained expressions} can be used describe trajectories satisfying specific constraints. It first shows how to express the most general nonlinear function passing through a single point in two distinct way, one additive and one rational. Then, functions with constraints on single, two, and multiple points are introduced. This capability allows to express functions to solve linear differential equations with no more need to add equality constraints (the ``subject to:'' expressions) as all the constraints

15:10 **AAS 17-264** **Stability of permanent rotations of a heavy asymmetric gyrostat**

Antonio Elipe, Centro Universitario de la Defensa. Zaragoza; Manuel Iñarrea, Universidad de la Rioja; Victor Lanchares, Universidad de la Rioja; Ana Pascual, Universidad de la Rioja

We consider the motion of a gyrostat under the attraction of a Newtonian field. For this problem, we obtain the possible permanent rotations, that is, the equilibria of the system.

The stability of those permanent rotations is analyzed by means of the Energy-Casimir method. We are able to give necessary and sufficient conditions for some of the permanent rotations. The geometry of the gyrostat and the value of the gyrostatic moment are relevant in order to get stable permanent rotations. Moreover, it seems that the necessary conditions are also sufficient, but, however, this fact can only be proved partially.

15:30 **Afternoon Break**

15:50 **AAS 17-285** **MINIMUM POWER SLEWS AND THE JAMES WEBB SPACE TELESCOPE**

Mark Karpenko, Naval Postgraduate School; Harleigh Marsh, UC Santa Cruz; Qi Gong, University of California, Santa Cruz

Power is a precious commodity in space flight. Many authors have thus utilized proxies for reaction wheel power to design minimal effort slews. Proxies are used because the power input equation is non-smooth. In this paper we show that a smooth cost functional for reaction wheel power can indeed be built and used to reduce the energy requirements for a typical large-angle slew of the James Webb Space Telescope. The energy reduction (>20%) is obtained by finding a minimum power momentum distribution that achieves the necessary control effort while simultaneously reducing power input to the individual wheels.

16:10 **AAS 17-300** **ADAPTIVE SAILCRAFT ATTITUDE STABILIZATION VIA PHOTONIC PRESSURE TORQUE**

Erik Proano, Embry-Riddle Aeronautical University; Dongeun Seo, Embry-Riddle Aeronautical University

The atttide control problem of the sailcraft is addressed focusing on the usage of a ground-based laser beam. Due to the characteristics of the sailcraft dynamics, the attitude response is slow and accompanied by the slow change in the moment of inertia tensor. The proposed control method is based on the non-certainty equivalent adaptive control principle to cope with the system parameter change which is proven to be robust to the external disturbances. The proposed controller is demonstrated through numerical simulations to show the control performance under system parameter uncertainties.

16:30 **AAS 17-302** **The Vibration and Orientation Integrated Control Method for Satellite Optical Payload**

Mou Li; Yao Zhang, Beijing Institute of Technology; Yue Zang

With the development of aerospace missions, the optical payload demands higher attitude accuracy and stability of satellite.To improve the imaging quality of the optical payloads, an active-passive integrated vibration isolation platform is implemented to isolate the vibration and achieve optical payload pointing control. In this paper, a vibration and orientation integrated control method is exposed basing on the platform. And the influence of some factors on the control accuracy is analyzed such as strut stroke precision and measurement errors of a platform. The control method achieved optical payload rapid orientation after large-angle attitude rapid maneuver with a satellite.

16:50 AAS 17-307 Fault Tolerant Control for Spacecraft Assembled with SGCMGs based on the Fault Decoupling

Fuzhen Zhang; Lei Jin, Beihang University; Shijie Xu, Beihang University

As for the spacecraft with SGCMGs, a fault tolerant control algorithm is proposed based on the fault decoupling in the following steps: first, the control torque of the spacecraft can be given without considering the fault. Then, the command gimbal rate can be obtained using the steering laws. Finally, a fault tolerant controller for each SGCMG is designed to track the command gimbal rate. In this way, the high-dimensional coupling actuator FTC problem can be decoupled into multiple one-dimensional FTC problems which greatly simplifies the controller design process. The controller can achieve attitude asymptotic stability on fault or fault-free condition.

17:10 AAS 17-373 The Eccentric Case of a Fast-Rotating, Gravity-Gradient-Perturbed Satellite Attitude Solution

Noble Hatten, The University of Texas at Austin; Ryan Russell, The University of Texas at Austin

A closed-form perturbation solution for the attitude evolution of a fast-rotating, triaxial space object in an elliptical orbit is presented. The solution takes into account gravity-gradient torque and is derived using the Lie-Deprit method. The formulation builds on the earlier implementation of Lara and Ferrer, which assumes a circular orbit. Additionally, several numerical analyses are presented to more completely assess the utility of the solution. These studies vary the small parameter of the perturbation procedure, analyze the assumption of fast rotation, and apply the solution to a tumbling rocket body.

17:30 AAS 17-513 MIN-MAX REPETITIVE CONTROL DESIGN FOR NON-MINIMUM PHASE SYSTEMS FROM NOISY FREQUENCY RESPONSE DATA

Pitcha Prasitmeeboom, Columbia University; Richard Longman, Columbia University

Repetitive control (RC) aims to eliminate the effects of a periodic disturbance to a control system. Spacecraft applications include active vibration isolation from slight imbalance in CMG's or reaction wheels. Non-minimum phase systems present design challenges. Previous work develops a design to minimize the maximum error, formulated as quadratically constrained quadratic programming, which addresses the design difficulties. This paper studies the influence of noise in frequency response data when making this optimization, and addresses how one should pick design choices including frequency range for the optimality criterion and cutoff frequency of the FIR zero-phase low-pass filter, to improve the design.

Feb 8, 2017La Villita A

17 Earth and Lunar Missions

Co Chair: Zubin Olikara

8:00 **AAS 17-238** **Space-Enhanced Solar Power for Equatorial Regions**
Federica Bonetti, University of Glasgow, School of Engineering; Colin McInnes, University of Glasgow

This work examines the concept of solar reflectors in an earth orbit to provide solar farms on the ground with additional solar power. The design of the orbit is critical for the purposes of the mission: the reflector needs continuous access to the sun and the ground site simultaneously. For this scope, orbits with high-eccentricity will be considered to increase the visibility time of the reflector. Also, since the most convenient locations for solar power plants are about the equator, a suitable orbit should have very low inclination. This issue can be addressed exploiting the concept of heliotropic orbits.

8:20 **AAS 17-259** **MOON AGE AND REGOLITH EXPLORER (MARE) MISSION DESIGN AND PERFORMANCE**
Gerald Condon, NASA; David Lee, NASA/JSC; John M. Carson, NASA

On December 11, 1972, Apollo 17 marked the last controlled U.S. lunar landing and was followed by an absence of methodical in-situ investigation of the lunar surface. The Moon Age and Regolith Explorer (MARE) proposal provides scientific measurement of the age and composition of a relatively young portion of the lunar surface near Aristarchus Plateau and the first post-Apollo U.S. soft lunar landing. It includes the first demonstration of a crew survivability-enhancing autonomous hazard detection and avoidance system. This report focuses on the mission design and performance associated with the MARE robotic lunar landing subject to mission and trajectory constraints.

8:40 AAS 17-267 Targeting Cislunar Near Rectilinear Halo Orbits (NRHOs) for Human Space Exploration

Jacob Williams, NASA Johnson Space Center; David Lee, NASA/JSC; Ryan Whitley, NASA; Kevin Bokelmann, University of Texas at Austin; Diane Davis, a.i. solutions, Inc.; Christopher Berry, NASA

Part of the challenge of charting a human exploration space architecture is finding locations to stage missions to multiple destinations. To that end, a specific subset of Earth-moon halo orbits, known as Near Rectilinear Halo Orbits (or NRHOs) are evaluated. In this paper, a systematic process for generating full ephemeris based ballistic NRHOs is outlined, different size NRHOs are examined for their favorability to avoid eclipses, the performance requirements to and from the NRHO are calculated, and disposal options are evaluated. Combined, these studies confirm the feasibility of cislunar NRHOs to enable human exploration in the cislunar proving ground.

9:00 AAS 17-290 DESIGN OF LOW-THRUST TRANSFER ORBIT TO EARTH-MOON LAGRANGE ORBIT VIA ELECTRIC DELTA-V LUNAR GRAVITY ASSIST

Toshinori Ikenaga, Japan Aerospace Exploration Agency

The ISECG addresses the use of Cislunar habitat for future space exploration. In the current synario, two types of Cislunar transfer scheme are considered i.e., in-direct transfer and Weak Stability Boundary transfer. The former case requires roughly 500 m/s order of delta-V however the time-of-flight from is practically short i.e, roughly 5~7 days. On the other hand, the latter case will significantly decrease the required delta-V, however the time-of-flight will be order of 6 months. Considering such situation, this paper focuses on low-thrust transfer orbit desigin to Earth-Moon Lagrange point to fullfil the significant gap between the two transfer methods.

9:20 AAS 17-319 The Lunar IceCube Mission Challenge: Attaining Science Orbit Parameters from a Constrained Approach Trajectory

David Folta, NASA Goddard Space Flight Center; Natasha Bosanac, Purdue University; Andrew Cox, Purdue University; Kathleen Howell, Purdue University

Targeting specific lunar science orbit parameters from a concomitant Sun-Earth/Moon system trajectory presents numerous challenges for CubeSats. While the concept of ballistic lunar capture is well-studied, achieving and controlling the time evolution of the orbital elements to satisfy mission constraints is especially problematic when the spacecraft is equipped with a low-thrust propulsion system. Satisfying these orbit requirements is critical to the success of the Lunar IceCube mission, a 6U CubeSat that will prospect for water and other lunar volatiles. This paper will present trajectory design strategies for achieving a lunar orbit subject to mission constraints and significant propulsive limitations.

9:40 **AAS 17-333** **DARE MISSION DESIGN: LOW RFI OBSERVATIONS FROM A LOW-ALTITUDE FROZEN LUNAR ORBIT**

Laura Plice, Metis Technology Solutions; Ken Galal; Jack Burns, University of Colorado Boulder

The Dark Ages Radio Experiment (DARE) seeks to study the cosmic Dark Ages approximately 80 to 420 million years after the Big Bang. Observations require truly quiet radio conditions, shielded from Sun and Earth EM emissions, on the far side of the Moon. DARE's science orbit is a frozen orbit with respect to lunar gravitational perturbations. The altitude and orientation of the orbit remain nearly fixed indefinitely without maintenance. DARE's observation targets avoid the galactic center and enable investigation of the universe's first stars and galaxies.

10:00 **Morning Break**

10:20 **AAS 17-395** **Stationkeeping Methodologies for Spacecraft in Lunar Near Rectilinear Halo Orbits**

Davide Guzzetti, Purdue Univeristy; Emily Zimovan, Purdue Univeristy; Kathleen Howell, Purdue University; Diane Davis, a.i. solutions, Inc.

Near Rectilinear Halo Orbits (NRHO), a subset of halo orbits characterized by favorable stability properties, are strong candidates for a future inhabited facility in the lunar vicinity. In this paper, two low-cost, reliable, stationkeeping strategies for maintaining long-term NRHO-like behavior in the ephemeris regime are investigated. Orbit determination errors, orbital perturbations, noise, and missed burns are incorporated into the high-fidelity simulation environment. As a complement, a real-time warning in the event of a diverging path and eclipse avoidance maneuvers are presented.

10:40 **AAS 17-456** **Trajectory Design for the Lunar Polar Hydrogen Mapper Mission**

Anthony Genova, NASA; David Dunham, KinetX, Inc.

The presented trajectory was designed for the Lunar Polar Hydrogen Mapper (LunaH-Map) 6U CubeSat, which was awarded a ride on SLS with EM-1 via NASA HQ's 2015 SIMPLEX proposal call. After deployment from EM-1's disposal stage (which is planned to enter heliocentric space via a lunar flyby), the LunaH-Map CubeSat will alter its trajectory via its low-thrust ion engine to target a lunar flyby that yields a Sun-Earth-Moon weak stability boundary transfer to set up a ballistic lunar capture. Finally, the orbit energy is lowered to reach the required quasi-frozen science orbit with perilune above the lunar south pole.

Feb 8, 2017La Villita B

18 Navigation

Co Chair: Renato Zanetti

8:00 AAS 17-230 **Small Body Navigation and Gravity Estimation using Angle and FDOA Observables**

Jeroen Geeraert, University of Colorado at Boulder CCAR; Jay McMahon, University of Colorado; Siamak Hesar, University of Colorado

In this proof of concept study we examine the use of angles, namely azimuth and elevation in addition to Frequency Difference of Arrival (FDOA) measurements to estimate the gravity field of 433 Eros. FDOA is a double differenced observable therefore any translation oscillation errors in the beacons and receiver errors in the main satellite cancel. This is the motivation to explore the potential use of FDOA, cheaper components may be used as measurement biases and errors would not affect performance unlike other observables such as range or range-rate/Doppler.

8:20 AAS 17-329 **A DEEP LEARNING APPROACH FOR OPTICAL AUTONOMOUS PLANETARY RELATIVE TERRAIN NAVIGATION**

Tanner Campbell, University of Arizona; Roberto Furfaro, The University of Arizona; Richard Linares, University of Minnesota; David Gaylor, University of Arizona

Autonomous relative terrain navigation is a problem at the forefront of space missions involving close proximity operations without any definitive answer. There are techniques to cope with this issue using both passive and active sensors, but almost all require very sophisticated dynamical models. Convolutional Neural Networks (CNNs) trained with images rendered from a digital terrain map (DTM) can provide a way to side-step the issue of unknown or complex dynamics while still providing reliable autonomous navigation. The portability of trained CNNs allows offline training that can yield a matured network capable of on-board real-time position acquisition.

8:40 AAS THE EVOLUTION OF DEEP SPACE NAVIGATION: 2004-2006
17-325 *Lincoln Wood, Jet Propulsion Laboratory, Caltech*

The exploration of the planets of the solar system using robotic vehicles has been underway since the early 1960s. During this time the navigational capabilities employed have increased greatly in accuracy, as required by scientific objectives and enabled by technological improvements. This paper is the fourth in a chronological sequence dealing with the evolution of deep space navigation and covers the time interval 2004 to 2006. The paper focuses on the observational techniques that have been used to obtain navigational information, propellant-efficient means for modifying spacecraft trajectories, and the computational methods that have been employed, tracing their evolution through eleven planetary missions.

9:00 AAS Juno Navigation for Jupiter Orbit Insertion
17-459 *Paul Thompson, NASA / Caltech JPL; Shadan Ardalan, NASA / Caltech JPL; John Bordi, NASA / Caltech JPL; Nicholas Bradley, Jet Propulsion Laboratory; Davide Farnocchia; Yu Takahashi, Jet Propulsion Laboratory*

Juno arrived at Jupiter on 05 July 2016 UTC, achieving orbit with the execution of the Jupiter Orbit Insertion (JOI) maneuver. During the last several weeks of the approach to JOI, the dominant uncertainties were from the Jupiter barycenter ephemeris. We discuss the maneuver and orbit determination strategy for JOI, as well as the challenges of calculating a correction to the Jupiter barycenter ephemeris prior to achieving Jupiter orbit. And we compare the history of Jupiter barycenter ephemeris updates during approach to the ephemeris based on a reconstruction of the JOI flyby.

9:20 AAS B-plane Evolution Under Highly Non-Keplerian Dynamics
17-323 *Yu Takahashi, Jet Propulsion Laboratory; Davide Farnocchia; Paul Thompson, NASA / Caltech JPL; Nicholas Bradley, Jet Propulsion Laboratory; Shadan Ardalan, NASA / Caltech JPL; John Bordi, NASA / Caltech JPL*

The Juno spacecraft performed the successful Jupiter orbit insertion (JOI) maneuver on July 5th, 2016 UTC. The navigation team was positioned at JPL and guided the spacecraft on approach. In this paper we discuss the usage of the B-plane for orbit determination performance and how it is affected by the gravity perturbation from Jupiter. We will highlight the analytical uncertainty quantification and compare it against the numerical results. The actual Juno tracking data is used for the analysis and the rapid change in the B-plane definition around perijove is discussed.

9:40 AAS 17-331 JPL Navigation Support for the JAXA Akatsuki (Planet-C) Return to Venus

Mark Ryne, NASA / Caltech JPL; Neil Mottinger, NASA / Caltech JPL; Eunice Lau, NASA / Caltech JPL; Maximilian Schadegg, Jet Propulsion Laboratory; Cliff Helfrich, Jet Propulsion Laboratory; Paul Stumpf, NASA / Caltech JPL; Brian Young, Jet Propulsion Laboratory, California Institute of Technology.

This paper details the activities undertaken at JPL Navigation in support of the Akatsuki (a.k.a. Planet-C) mission's return to Venus. The JPL navigation team's role was to provide independent navigation support as a point of comparison with the JAXA generated orbit determination solutions. Topics covered will include a mission and spacecraft overview, small forces modeling, cruise, approach, and Venus phase orbit determination results, and the international teaming arrangement. Significant time will also be dedicated to discussion of preparations for the Venus orbit insertion maneuver, which was successfully executed on December 7, 2015.

10:00 Morning Break

10:20 AAS 17-358 Fringe Fitting for DOR Tones in geodetic VLBI

songtao han, Beijing Aerospace Control Center; Zhang Zhongkai

Spacecraft is usually equipped with DOR transponder to support high accuracy interferometric tracking. Some space agencies, such as ESA/NASA, adopt correlator based on phase locking or local correlation algorithm to process DOR tones. While geodesy and astronomy agencies usually deploy correlator(Difx,K5..), post-processing software (HOPS/AIPS..) mainly for quasar observation. As DOR tones vary narrow spectrum are totally different from quasar continuum spectrum, here comes the problem: is the fringe fitting still effective for DOR tones signal? In this paper, we discuss the fringe fitting algorithms suitable for DOR tones and make a comparison with experiment data.

10:40 AAS 17-489 OPTICAL NAVIGATION CONCEPT OF OPERATIONS FOR THE OSIRIS-REX MISSION

Coralie Jackman, KinetX Aerospace; Derek Nelson, KinetX, Inc.; Leilah McCarthy, KinetX, Inc.; Tiffany Finley, Southwest Research Institute; Andrew Liounis, NASA Goddard Space Flight Center; Kenneth Getzandanner; Peter Antreasian, KinetX, *Inc. ; Michael Moreau, NASA Goddard Space Flight Center*

The OSIRIS-REx sample return mission will begin proximity operations at asteroid Bennu in late 2018. Optical Navigation (OpNav), a sub-function of the Flight Dynamics System, uses information extracted from spacecraft images to assist in the orbit determination of the spacecraft. Star-based OpNav is utilized in early mission phases, before global imaging data and digital terrain maps are available. Once these maps are available, landmark navigation is utilized in order to achieve the required navigation performance requirements. This paper will discuss the optical navigation concept of operations for each mission phase, details about imaging plans, and operational OpNav techniques.

11:00 **AAS 17-529** **Orbit Determination analysis of Venus space probe "Akatsuki (Planet-C)"**
Tsutomu Ichikawa, Japan Aerospace Exploration Agency (JAXA)

A spacecraft orbiting Venus known as " Akatsuki ", has been launched on May 21, 2010 on H-IIA booster It arrived at Venus on December 7, 2010, but due to a malfunction of the thruster system, the Venus orbit insertion failed. Using the reaction control systems instead of the broken orbital maneuvering engine, the recovery maneuver was operated on December 7, 2015, and Akatsuki was finally inserted into an orbit around Venus with a 0.36 million km apoapsis and a 10.5 day. It is described the strategy, analysis, and evaluation for the determination of orbit around Venus in detail.

Feb 8, 2017La Villita C

19 Rendezvous and Proximity Operations II

Co Chair: Brandon Jones

8:00 **AAS 17-242** **Design of Bounded Relative Trajectories in the Earth Zonal Problem**
Nicola Baresi, University of Colorado Boulder; Daniel Scheeres, University of Colorado

The generation of a continuous set of bounded relative motions about an arbitrary satellite orbit is developed. This is done using a rigorous computational approach for finding the quasi-periodic orbits about an axis-symmetric Earth gravity field. The method also allows families of bounded trajectories to be found with specified nodal and orbital periods. This enables the precise design of constellations and clusters of orbits that never drift apart from each other under zonal harmonics perturbations.

8:20 **AAS 17-276** **Orbit Determination with Least-Squares and Flash LIDAR Measurements in Proximity to Small Bodies**

Ann Dietrich, University of Colorado Boulder; Jay McMahon, University of Colorado

Spacecraft missions to celestial small bodies involve many challenges, and the current relative optical navigation is performed on the ground and involves significant processing time. This research aims to expand spacecraft navigation autonomy through the use of a flash LIDAR instrument, which can provide upwards of thousands of altimetry measurements to its target. This paper continues previous OD work by solving for the spacecraft position directly with a least-squares algorithm and feeding this into a Kalman filter for orbit determination. The study also characterizes the position uncertainty from the least-squares algorithm and how the observation frequency affects the velocity estimation.

8:40 **AAS 17-402** **Adaptive Filtering for Maneuver-Free Angles-Only Navigation in Eccentric Orbits**

Joshua Sullivan, Space Rendezvous Laboratory, Stanford University; Simone D'Amico, Stanford University

This paper addresses the design of a novel estimation architecture that uses bearing angles obtained by a servicer spacecraft onboard camera to determine the relative orbit of a noncooperative target in eccentric orbit without requiring reconfiguration maneuvers. A new algorithm for initial relative orbit determination in eccentric J_2-perturbed orbits is developed for filter initialization. To address performance and stability issues arising from limited dynamical observability, the extended and unscented Kalman filters are leveraged to exploit nonlinearities in the system measurement model. An innovative design is pursued to adaptively tune filter process noise statistics online to mitigate errors due to dynamics mismodeling and linearization. The proposed algorithms are validated in high-fidelity simulation.

9:00 **AAS 17-411** **Safe Relative Motion Trajectory Planning for Satellite Inspection**

Gregory Frey, University of Michigan; Christopher Petersen, University of Michigan; Frederick Leve, Air Force Office of Scientific Research; Anouck Girard, University of Michigan; Ilya Kolmanovsky, University of Michigan

Safe trajectory planning for satellite inspection involves calculating an inspection path to be traversed by an inspector spacecraft in order to obtain information about a target spacecraft while satisfying constraints. The solution to this problem is complicated by dimensionality and, in the case of certain types of constraints, non-convexity. We report on three methods to calculate safe inspection paths to obtain information with reduced computational effort. Simulation results illustrate each approach and comparisons are made between the methods to highlight relative strengths and weaknesses.

9:20 AAS 17-474 A PURSUIT-EVASION GAME IN THE ORBITAL PLANE

Jhanani Selvakumar, The University of Texas at Austin; Efstathios Bakolas, The University of Texas at Austin

We consider a pursuit-evasion game of two spacecraft in the Hill's frame. In particular, we have a chief and a deputy spacecraft, and we aim to achieve positional coincidence between them within a user-specified tolerance. In this two-player zero-sum game, the chief spacecraft and the deputy spacecraft respond to each other's actions in an antagonistic manner. The chief aspires to maximize the time of capture while the deputy aims to minimize the same. For a circular orbit, we can precisely characterize the controllable sets and consequently the initial conditions that ensure capture of the chief by the deputy.

9:40 AAS 17-475 Analytic Solution of Perturbed Relative Motion With Zonal and Tesseral Harmonics

Bharat Mahajan, Texas A&M University; Srinivas R. Vadali, Texas A&M University; Kyle T. Alfriend, Texas A&M University

Tesseral and sectorial harmonics cause significant variations in the orbital elements, that are comparable to the effects of zonals. Their most significant effect is on the variation of mean anomaly of a satellite. In case of perturbed relative motion, slightly different variations in the mean anomalies of the two satellites due to tesserals can cause significant along-track drift errors. In this work, a complete relative motion STM including the perturbation effects of an arbitrary zonal and tesseral spherical harmonic is presented. No assumption on the small value of the eccentricity of the reference orbit is made for deriving the STM.

10:00 Morning Break

10:20 AAS 17-498 METHODS OF RELATIVE ORBIT ESTIMATION INVOLVING SOLUTION OF POLYNOMIAL SYSTEMS

Alan Lovell; Caroline Young; Chloe Baker; Kenneth Horneman, Barron Associates Inc.

This paper presents an approach to initial orbit determination that utilizes closed-form relative orbital dynamics solutions, whereby relative orbital states are expressed as polynomial combinations of the initial conditions. If the measurement-state relationships can also be cast in polynomial form, then the overall measurement equations to be solved constitute a system of polynomials. Several example scenarios are generated involving angles-only (line-of-sight) and range-only measurements. For each scenario, derivation of the polynomial system is clearly laid out, and a very stable algorithm is employed to solve the system. Methods of disambiguation are shown, for cases when multiple real solutions are obtained.

10:40 AAS 17-509 An Integrated Solution for Distributed Cooperative dynamic mission planning

WEINAN Wu, Harbin Institute of Technology; Naigang Cui, Harbin Institute of Technology; Jifeng Guo

This paper addresses the problems of autonomous task assignment and path planning for a fleet of heterogeneous spacecrafts in cooperative mission. In previous work many algorithms have almost run on centralized architecture and handle the task assignment decoupling with the path planning. This may result in poor solutions. Therefore, this paper investigates a novel integrated solution for spacecrafts to perform multiple consecutive tasks cooperatively based on distributed planning architecture. In a given scenario, the heterogeneous spacecrafts have different capabilities, kinematic constraints, etc. This paper presents details of the integrated solution which produces optimal assignment and trajectories for several given scenarios.

11:00 AAS 17-232 Robust Triad and Quad Generation Algorithms for Star Trackers

David Arnas, Centro Universitario de la Defensa - Zaragoza; Marcio A. A. Fialho, INPE - Instituto Nacional de Pesquisas Espaciais; Daniele Mortari, Texas A&M University

In Star Identification, some observations are not only generated by actual stars, but by debris, satellites, planets, or electronic noise, which makes the capability to discriminate stars from non-stars very important. Usually, a first identification attempt is performed on a group of observed stars (kernel) and, in case of failure, it is replaced until a kernel made of only actual stars is found. This work analyses kernel generator algorithms suitable for on-board implementation in terms of speed and robustness, for kernels of three and four stars. Three new kernel generator algorithms and two metrics for robustness evaluation are proposed.

Feb 8, 2017Pavo Real

20 Attitude Dynamics and Control II

Co Chair: Kyle DeMars

8:00 AAS 17-311 PERFORMANCE TESTS OF THE PYRAMID STAR-ID ALGORITHM WITH MEMORY ADAPTIVE K-VECTOR

Marcio A. A. Fialho, INPE - Instituto Nacional de Pesquisas Espaciais; Daniele Mortari, Texas A&M University; Leonel Perondi

This paper presents results obtained with a C/C++ implementation of the memory adaptive k-vector and other minor modifications in the Pyramid STAR-ID algorithm, including benchmark results of Pyramid run time versus the amount of memory allocated for the k-vector. This paper concludes with a discussion about the tradeoff relations between memory allocated for the k-vector and speed, and the impact of cache misses in modern processors for very long k-vectors.

8:20 AAS 17-312 NEW PRACTICAL RESULTS FOR FLAT-SPIN RECOVERY BY EQUATORIAL TORQUES

Jozef van der Ha, Consultant; Frank Janssens, Retired

The paper studies the motion of a spinning rigid asymmetric body under an equatorial torque (i.e., normal to spin axis). Through extensive simulations, starting from pure flat-spin motion, four types of motion are identified and visualized as zones within the plane formed by the two torque components. The zone "No Recovery" describes a new type of unstable motion. The zone "Slow flat spin recovery" gives new insights into the efficiency of a recovery strategy by an equatorial torque. For the zone "Fast Recovery" an analytical model involving Fresnel integrals gives an approximation of the asymptotic motion (on a cylinder).

8:40 AAS 17-313 Rethinking Orthogonal Reaction Wheel Configurations for Small Satellites

Jeffery King, U.S. Naval Academy; Mark Karpenko, Naval Postgraduate School

Rigid-body agility is limited by the maximum torque and orientation of the reaction wheels. Maximizing the inscribed sphere of the torque envelope can underestimate the true capability of the system because spacecraft inertia properties are not considered. We show that simple reorientation of the reaction wheel assembly while maintaining orthogonality can increase agility while maintaining spherical acceleration limits. This paper utilizes the associated concept of the agility envelope to develop analytical equations for finding ideal reaction wheel orientations that provide up to 40% more capability than conventional methods. The equations and corresponding design curves are presented for typical small satellites.

9:00 **AAS 17-324** **Bayesian Attitude Estimation on SO(3) with Matrix Fisher Mixtures**
Shankar Kulumani, George Washington University; Taeyoung Lee, George Washington University

This paper presents a Bayesian attitude estimation for a rigid body on the special orthogonal group.
The matrix Fisher distribution provides a compact form of unimodal probability densities for attitude uncertainty, and it has been utilized in attitude estimation on the special orthogonal group.
This paper aims to extend such results to a general class of uncertainties with a mixture of matrix Fisher distributions.
Stochastic attitude estimators are constructed directly on the special orthogonal group with matrix Fisher mixtures, and it is shown that the proposed approach is particularly useful for challenging attitude estimation problems with arbitrarily large uncertainties.

9:20 **AAS 17-340** **Geometric Switching Scheme for Attitude Control of an Underactuated Spacecraft with Two Control Moment Gyros**
Christopher Petersen, University of Michigan; Frederick Leve, Air Force Office of Scientific Research; Ilya Kolmanovsky, University of Michigan

A switching feedback controller is developed for the attitude control of an underactuated spacecraft equipped with two control moment gyros (CMGs). The overall method exploits the separation of the system states into inner-loop base variables and outer-loop fiber variables. The base variables, which in this paper are the gimbal angles, track periodic reference trajectories. The amplitude of the base variables is governed by parameters that are adjusted to induce an appropriate change in the fiber variable, which in this paper is the attitude of the spacecraft described by SO(3), towards the desired pointing configuration.

9:40 **AAS 17-343** **Repetitive Model Predictive Controller Design Based on Markov Parameters**
Jianzhong Zhu, Columbia University; Richard Longman, Columbia University

Repetitive Control (RC) and Iterative Learning Control (ILC) are methods to converge to zero tracking error in feedback control systems. Spacecraft applications include vibration isolation of fine pointing equipment. Model Predictive Control (MPC) algorithms use a model of the process to obtain the control signal by minimizing an objective function. This paper investigates how RC problems can be addressed by the MPC approach, making use of design methods from ILC. A new MPC design method with a penalty on the change of the command is developed for periodic signal tracking or periodical noise cancelation, i.e. jitter control.

10:00 **Morning Break**

10:20 **AAS 17-292** **Performance Analysis of Spacecraft Maneuver to Calibrate Attitude Determination Subsystem**

SooYung Byeon, Satrec Initiative; Dongwook Koh, Satrec Initiative; Hyunwook Woo, Satrec Initiative; Amer AlSayegh, Mohammed Bin Rashid Space Centre

This paper presents well-designed spacecraft maneuver to calibrate attitude determination subsystem and its performance analysis results. In-orbit calibration for attitude sensors is critical issue to achieve high performance of attitude determination subsystems. The purpose of the spacecraft calibration maneuver is to distinguish the attitude errors occurred by estimating parameters such as gyro misalignment, scale factor error, and star tracker misalignment from that of other error sources. In other words, well-designed calibration maneuver makes estimating parameters observable. Simulations and in-orbit satellite data sets from DubaiSat-2 will be suggested at the end of paper to analysis performance of various calibration maneuvers.

10:40 **AAS 17-351** **The dynamic analysis of vibration isolation system based on magnetic suspension techniques and the application on the satellites**

Chao Sheng

The vibration isolation platform is widely used to isolate the micro vibration with high frequency caused by the actuators on satellites. The traditional vibration isolation platform has difficulty in achieving fast maneuvering and fast stabilization attitude control. In this work, a new kind of vibration isolation platform whose actuators are based on the magnetic suspension techniques is presented. This paper builds the dynamic model of the vibration isolation platform and studies its dynamic characteristics. Then its application on the satellites is analyzed. The accuracy is validated through numerical simulations of an attitude control loop using the vibration isolation platform.

11:00 **AAS 17-376** **A Semianalytical Technique for Six-Degree-of-Freedom Space Object Propagation**

Noble Hatten, The University of Texas at Austin; Ryan Russell, The University of Texas at Austin

A middle ground between three- and six-degree-of-freedom (3DOF and 6DOF, respectively) space object state prediction is proposed, in which the translational equations of motion are propagated numerically using approximate attitude predictions obtained via a closed-form perturbation solution. The capabilities of this semianalytical “hybrid” technique are illustrated using a specific attitude solution. In numerical examples, the hybrid method produces position predictions one or more orders of magnitude more accurate than a 3DOF cannonball propagation while requiring approximately one third the CPU time of a full 6DOF propagation for certain accuracy tolerance levels. Speedups are shown to increase as body rotation rate increases.

11:20 AAS 17-386 Time-optimal reorientation of an autonomous agile earth observing satellite

Mingwei Yin, Tsinghua University; Hongwei Yang, Tsinghua University; Hexi Baoyin, Tsinghua University

This paper proposes a rapid parameterized algorithm for the time-optimal reorientation of an autonomous agile satellite which is presently studied by China. The reorientation problem is reformulated by the modified Rodrigues parameters. The attitude angles, angular velocities, available torques and real-time meteorological information are all modeled analytically in the dynamical model. Instead of solving a two-point boundary value problem, it is described as a constrained nonlinear programming problem, which can be optimized by Radau Pseudospectral method. Numerical simulations illustrate that the algorithm is fast enough for the online computation onboard.

11:40 AAS 17-388 High Accuracy Attitude Determination Estimator System for IRASSI Interferometer Spacecraft

Divya Bhatia, Institute of Flight Guidance, Technische Universität Carolo-Wilhelmina zu Braunschweig; Ulf Bestmann, Institute of Flight Guidance; Peter Hecker, Institute of Flight Guidance, Technische Universität Braunschweig

High accuracy attitude determination is becoming a norm for future space missions. Hence, this work describes development of an Attitude Determination Estimator System (ADES) which achieves an unprecedented stringent attitude estimation accuracy of 0.04 arcsec. This is accomplished by carefully selected high accuracy commercial-off-the shelf (COTS) sensors and implementing state-of-the-art optimal attitude estimation algorithm for sensor data fusion in MATLAB. During fine-pointing mission mode of IRASSI, data from two simultaneously operating star trackers are fused with gyroscope via a Multiplicative Extended Kalman Filter (MEKF). During Initial Attitude Acquisition mode, measurements from Sun Sensor and Gyroscope are fused via MEKF.

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21 Asteroid Missions III

Co Chair: Brent Barbee

13:30 AAS 17-357 TIME-DELAYED FEEDBACK CONTROL OF HOVERING AND ORBITING ABOUT ASTEROIDS

Li Haiyang, Tsinghua University; Hexi Baoyin, Tsinghua University

In asteroid exploration, hovering and orbiting the asteroid are necessary before further operation. Dynamic characteristics about asteroids are mainly equilibrium points and periodic orbits. Hovering on the natural equilibrium points and orbiting on the natural periodic orbits about asteroids are efficient and economical. However, due to the presence of orbit-determination and model-uncertainly error, the motion will be extremely difference. Time-delayed feedback control is used to solve this problem. Orbit-determination and model-uncertainly errors are formulated. Adaptive gain matrix algorithm and delay time determination method are proposed. Simulations prove that control method presented in this paper is effective.

13:50 AAS 17-371 From Simplified to Complex Small-Body Models: Sensitivity Analysis of Periodic Orbit Sets

Alex Pini, a.i. solutions, Inc.; Benjamin Villac, a.i.solutions, Inc.; Rodney Anderson, NASA / Caltech JPL

A previous study introduced the use of clustering as a tool to support mission designers in organizing sets of ballistic orbits for small-body missions. In that study, periodic orbits generated in simplified dynamical models were examined, leading to the identification of attractive characterization orbits. This paper furthers that study by analyzing the sensitivity of these periodic orbits when exposed to various perturbations. In particular, the issue of transferring the initial conditions to higher fidelity models and the characterization of the resulting behavior is explored in light of the underlying dynamics. The asteroid 2008 EV5 is selected as a test case.

14:10 AAS 17-377 Solar Sail Orbital Motion About Asteroids and Binary Asteroid Systems

Jeannette Heiligers, Delft University of Technology; Daniel Scheeres, University of Colorado

Solar radiation pressure (SRP) is often considered an undesirable effect, especially for missions to small bodies like asteroids and binary asteroid systems. However, this paper exploits SRP in the form of solar sails to generate artificial equilibrium points (AEPs) and displaced periodic orbits in these systems. The results include hovering points at a single asteroid as well as orbits around these AEPs. In the binary system, we present novel families of solar sail orbits above the binary system's orbital plane. All orbits presented allow unique, geostationary-equivalent vantage points from where to monitor the asteroid(s) over extended periods of time.

14:30 **AAS 17-380** **Near Earth Asteroids Capture to Lunar Orbits Using Resonant Gravity Assists**
Changchun Bao; Hongwei Yang, Tsinghua University; Hexi Baoyin, Tsinghua University

First step of capturing NEAs is to transfer them from the heliocentric orbit to the geocentric orbit. The transfer is calculated in the Sun-NEA two-body model where an impulse is executed on the NEAs to make them approach the Moon for gravity assist. The second step is the capture by the Moon with resonant gravity assist where an impulse is applied at the apogee of the asteroid to decrease the velocity relative to the Moon. The final step is to insert the NEAs into the orbit of the Moon by executing braking maneuver.

14:50 **AAS 17-397** **Dynamics of a Spacecraft Orbiting A Binary Asteroid**
Thais Oliveira, INPE - National Institute For Space Research; Antonio Fernando Bertachini Prado, INPE

An analytical and numerical study is performed for a spacecraft orbiting a binary asteroid. The mathematical model for the binary asteroid varies from two point masses to full irregular bodies. An initial orbit of the spacecraft around one of the asteroids is defined by giving three Keplerian elements of its orbit: semi-major axis, eccentricity and inclination. Then, numerical integrations considering different shapes for both asteroids will map the orbits, in particular measuring the lifetime of the orbits before a collision with the asteroid. Maps will show how the duration of each orbit as a function of the initial Keplerian elements.

15:10 **AAS 17-404** **Gravitational Potential Modeling of Near-Earth Contact Binaries**
Stephanie Wood, University of Vermont; Jason Pearl, University of Vermont; Darren Hitt, University of Vermont

The ability to observe small celestial bodies has grown drastically over the last decade. The increase in interest for these bodies has increased demand for higher fidelity trajectory simulations in order to assure mission success. Most methods that are available for simulating trajectories about asymmetric bodies assume they are of uniform density. Here we propose a modification to two well-known methods: the mascon model and the spherical harmonic series approximation, for use in simulating trajectories about variable density bodies. In particular, we will look at contact binaries which are bodies consisting of two different densities.

15:30 **Afternoon Break**

15:50 **AAS 17-442** **Asteroid Gravitational Models Using Surface-Concentrations**
Jason Pearl, University of Vermont; Darren Hitt, University of Vermont

The polyhedral potential model has been used extensively to approximate the irregular gravity field of asteroids and comets using a polygonal mesh. In the present work a simplification of the polyhedral potential model is presented in which each face polygonal mesh is approximated as a surface-concentration. The accuracy and computational efficiency of the simplified model is then compared to that of the polyhedral potential model. Results indicate that the surface concentration model is on the order of 6 times faster than the polyhedral potential methods and only marginally less accurate even at close proximity.

16:10 **AAS 17-462** **Numerical Simulation of N-Body Asteroid aggregation with GPU-parallel hierarchical treecode algorithm**
Emmanuel Blazquez, Politecnico di Milano; Fabio Ferrari, Politecnico di Milano; Michèle Lavagna, Politecnico di Milano

Significant evidence has shown that asteroids with dimensions exceeding few hundreds of meters are gravitational aggregates of smaller bodies bound together only by gravitational forces. The study of such complex bodies is motivated by the recent efforts by space agencies to intercept or redirect near-Earth asteroids. The development of models for orbital dynamics about gravitational aggregates and complex gravity fields around irregular object is therefore required. This work presents a new modeling and implementation of a N-body numerical solver using a GPU-parallel Barnes-Hut implementation to evaluate the effects of gravitational interactions and the Chrono::Engine multi-physics simulation engine to simulate collisions between bodies.

Feb 8, 2017La Villita B

22 Orbital Debris

Co Chair: Puneet Singla

13:30 AAS 17-233 CNES ACTIVITES ON POLYNOMIAL CHAOS EXPANSION FOR UNCERTAINTY PROPAGATION

Vincent Morand, CNES; Pierre Mercier; Guillaume Prigent; Emmanuel Bignon; Pietro Congedo, INRIA

Dealing with initial uncertainties, or models uncertainties, and their evolution over time has become a point of greater interest over the last years. In particular, the increasing number of space debris strengthens the need for more efficient technics for risk assessment, both on orbit (collision risk) and on ground (casualty risk). One of the most common non-intrusive methods for uncertainty propagation is called Polynomial chaos expansion (PCE). The paper will briefly review some fundamentals of the PCE and the framework that have been adopted during the study. Test cases will be presented, covering concrete day-to-day work of a spaceflight engineer.

13:50 AAS 17-237 Observability Analysis Applied To Artificial Near-Earth Objects With Noise

Alex Friedman, Purdue University; Carolin Frueh, Purdue University

Observability analysis is a method for determining whether a chosen state of a system can be determined from measurements. A system is better understood with information gained from observability analysis, leading to improved sensor tasking for observation of orbital debris and better control of active spacecraft. Pre-whitening is implemented to include realistic measurement noise in the observability analysis of artificial near-Earth objects. In order to compare the observability analysis results with and without realistic measurement noise, quantitative measures of observability are investigated and implemented. Using measures of observability, the effect of realistic measurement noise on observability analysis results is determined.

14:10 AAS 17-244 Is the Probability of Collision of a Spacecraft Traversing Through the Earth's Debris Environment Described by a Poisson Distribution?

Ken Chan, Chan Aerospace Consultants

This paper answers the question whether the probability of collision of a spacecraft traversing through Earth's debris environment is described by the Poisson distribution when given the debris collision fluxes obtained from the NASA ORDEM 3.0, ESA MASTER and “N=IJK” Models. The N=IJK Model is applied to the steady state cloud of Earth-orbiting debris objects. It accounts for the actual debris population with actual inclined orbits, thus resulting in a variation of debris density with latitude and altitude. In all previous published literature, whenever the Poisson distribution was invoked, the reason for justification was similarity to the Kinetic Theory of Gases Model.

14:30 AAS 17-245 Comparison of Debris Collision Fluxes for the International Space Station

Ken Chan, Chan Aerospace Consultants; Wei-Ping ZHOU, National Astronomical Observatories, Beijing, China

This paper is concerned with the calculation of the debris fluxes experienced by the International Space Station (ISS) traversing through a cloud of orbiting debris. It considers two cases of modeling the orbits of the debris within a thin spherical shell straddling the ISS orbit: (1) the debris objects have "almost" circular orbits; (2) all the actual debris orbits are used. It accounts for the actual debris population with various inclined orbits, thus resulting in a variation of debris density with latitude. The number of debris objects per year is compared to that obtained by the NASA ORDEM 3.0 Model.

14:50 AAS 17-298 Environmental estimation on sub-millimeter-size debris using in-situ measurement data

Masahiro Furumoto, Kyushu University; Shin'ya Nakano, The Institute of Statistical Mathematics; Koki Fujita, Kyushu University; Toshiya Hanada, Kyushu University

Space debris smaller than 1 mm in size still have enough energy to cause a fatal damage on a spacecraft, but such tiny debris cannot be followed or tracked from the ground. Therefore, IDEA the project for In-situ Debris Environmental Awareness, which aims to detect sub-millimeter-size debris using a group of micro satellites, has been initiated at Kyushu University. This study proposes data assimilation method for estimating sub-millimeter-size debris environment using in-situ measurement data and smoothed distribution of traced objects. Numerical simulation verified that the proposed method could estimate simple distribution of tiny debris.

15:10 AAS 17-363 Design of a synthetic population of geostationary space debris by statistical means

Alexis Petit, University of Namur; Daniel Casanova, Centro Universitario de la Defensa; Morgane Dumont, University of Namur; Anne Lemaitre, University of Namur

We can observe and track objects with size about 1 meter in the geostationary region by

telescope means. However, a huge population of space debris still remains unknown for us. In this work, we propose to generate a synthetic (artificial) population of individual space debris, whose global characteristics are the same as the real one. We compare two approaches; the first one, using a combination of orbit propagators, fragmentation models, and historical data, and the second one, using an Iterative Proportional Fitting (IPF) procedure, which allows to reconstruct the current population from partial data

15:30 **Afternoon Break**

15:50 **AAS 17-441** **Spacecraft Electrostatic Force and Torque Expansions yielding Appropriate Fidelity Measures**

Joseph Hughes; Hanspeter Schaub, University of Colorado

Charged spacecraft experience electrostatic forces and torques from both charged neighboring spacecraft and the local space environment itself. This paper presents a novel expansion method for force and torque prediction called Appropriate Fidelity Measures (AFMs). They provide analytical insight and predictive capability of the electrostatic forces acting on general spacecraft shapes with a conducting outer surface by truncating a binomial series for the differential force in the inter-craft situation.

16:10 **AAS 17-461** **Extraction and Assignment of Tumbling Asteroid and Defunct Satellite Rotation Periods from Simulated Light-Curve Observations**

Conor Benson, University of Colorado Boulder; Daniel Scheeres, University of Colorado

Fourier transform analysis and Fourier series fitting methods for extracting the rotation periods of tumbling bodies from simulated light-curves are discussed. Methods leveraging the analytical dynamics and body mass distribution, shape, and orientation information are also explored for assigning extracted periods to the rotation and precession motion. These methods are then tested on simulated tumbling light-curves with all parameters known a priori for verification. While extraction was challenging, dynamical relationships and body information significantly constrained the possible periods, sometimes enough to yield conclusive solutions. These assignment methods are suited for analyzing light-curves of asteroids and defunct satellites with roughly known moments of inertia and geometries.

16:30 **AAS 17-483** **Electrostatically Charged Spacecraft Formation Estimation Using Linearized Relative Orbit Elements**

Trevor Bennett, University of Colorado; Hanspeter Schaub, University of Colorado

Touchless methods of actuating and detumbling large Earth-orbiting objects are of increasing importance to active satellite servicing and debris mitigation strategies. Electrostatic detumble, the process of using electrostatic interaction between two spacecraft, is able to touchlessly detumble large targets in Geostationary orbit. This study develops the estimation approach to obtain the electrostatic potential of the target object using only relative motion measurements. The sensitivity to electrostatic perturbations are developed using the Linearized Relative Orbit Elements relative motion description. The analytical conclusions are validated using a two-time-scale Kalman filter numerical simulation.

16:50 AAS 17-501 DE-ORBIT TIME OF ON-ORBIT DEBRIS FOR LASER-BASED REMOVAL METHODS

Prathyusha Karampudi, Wichita State University; Atri Dutta, Wichita State University

The amount of space debris in the near-Earth space environment poses a major challenge for current and future space missions, and active debris removal missions are necessary for safe space operations. This paper focusses on the laser-based removal of on-orbit debris. We consider the momentum change of the debris due to laser ablation and investigate the de-orbit times for debris having cubic or spherical shape. Our focus is on modeling the de-orbiting process as a low-thrust transfer under the action of continuous perturbing force due to laser. We present numerical results for a variety of starting orbits for the debris.

Feb 8, 2017La Villita C

23 Formation Flying and Relative Motion

Co Chair: Rodney Anderson

13:30 AAS 17-202 Comparison of Relative Orbital Motion Perturbation Solutions in Cartesian and Spherical Coordinates

Eric Butcher, University of Arizona; Ethan Burnett, University of Arizona; Alan Lovell

Previously shown perturbation approaches for unperturbed spacecraft relative motion solutions in Cartesian and spherical coordinates, in which both the chief eccentricity and the normalized separation were treated as order epsilon, are extended in this work to allow for higher chief orbit eccentricity. The relative accuracies of the solutions obtained in Cartesian versus spherical coordinates are explored for a wide range of relative orbit scenarios and perturbation orders. While the use of spherical coordinates eliminates many of the secular terms in the Cartesian solution and extends the range of in-track separations, certain scenarios are found to result in less accuracy.

13:50 AAS 17-209 A CAPTURE METHOD OF ORBITAL NET-CAPTURE SYSTEM BASED ON COOPERATIVE FORMATION FLYING CONTROL

Liangming Chen; Yanning Guo, Harbin Institute of Technology; Chuanjiang Li

To cope with the space debris removal mission, a capture method based on spacecraft formation flying is investigated for the orbital net-capture system. Firstly, the relative orbit motion dynamics for each payload are modeled in the local-vertical and local-horizontal rotating frame. Secondly, the flying capture trajectory for each payload is planned by the four-order polynomial. Then, a cooperative saturated PD control algorithm with computed feedforward is proposed such that all payloads can track the planned flying trajectories. This realizes the closed-loop orbital net-capture process. Finally, the simulation example of four payloads installed at the net capturing one static space debris

14:10 AAS 17-291 Constrained Low-Thrust Satellite Formation-Flying Using Relative Orbit Elements

Lukas Steindorf, Space Rendezvous Laboratory, Stanford University ; Simone D'Amico, Stanford University; Julian Scharnagl, Zentrum für Telematik e.V.; Florian Kempf, University of Würzburg; Klaus Schilling, University of Würzburg

This paper proposes a continuous low-thrust guidance and control strategy for satellite formation-flying. Stabilizing feedback based on mean relative orbit elements and Lyapunov theory is used. A novel feedback gain matrix inspired by the fuel-optimal impulsive solution is designed to achieve near-optimal fuel consumption. A reference governor is developed to autonomously guide the spacecraft through the relative state-space in order to allow for arbitrarily constrained satellite formations. Constraints include desired maximum thrust levels, time constraints, passive collision avoidance and locally constrained state-space areas. Keplerian dynamics are leveraged to further decrease fuel consumption.

14:30 AAS 17-328 Rectification of the Second-Order Solution for Spacecraft Relative Motion

Andrew Sinclair, Auburn University; Richard Erwin, Air Force Research Laboratory

Whereas the linear solution for spacecraft relative motion is often used in rendezvous and proximity missions, study of the second-order solution has been motivated by a desire for greater accuracy. An observed property of this solution is that treating a point along the solution as a new initial condition produces an alternate solution that differs from the original solution. This motivates a rectification process for long-term evaluation of the second-order solution. At intervals, the instantaneous solution is defined as a new initial condition for continued propagation of the solution. This process can provide greater accuracy in predicting spacecraft relative motion.

14:50 AAS 17-336 SPACECRAFT PROXIMITY FORMATION FLYING: A HOMOTOPY BRIDGE FROM ENERGY-OPTIMAL TO FUEL-OPTIMAL SOLUTIONS USING LOW-THRUST

Marco Gulino, The University of Texas at Austin; Maruthi Akella, The University of Texas at Austin

This paper focuses on finding the low-thrust fuel optimal solution to a class of spacecraft formation proximity operations subject to path constraints. The mission is for a deputy spacecraft to perform a surveying orbit relative to a chief within a prescribed period, without violating a no fly zone represented by a sphere centered on the chief. Clohessy-Wiltshire equations are used, together with the controllability Gramian of the resulting linear system, to obtain an analytical solution to the energy optimal problem. A homotopic approach subsequently shown to serve as an effective bridge from the energy-optimal solution toward the fuel optimal solution.

15:10 AAS 17-353 RIGID BODY CONSENSUS UNDER RELATIVE MEASUREMENT BIAS

Devyesh Tandon, Indian Institute of Technology Bombay; Sukumar Srikant, Indian Institute of Technology Bombay

We study the problem of achieving position consensus in a multi-agent rigid-body system operating under measurement bias. It is assumed that the agents measure relative positions of each other with a constant sensor bias. A Lyapunov function based approach is utilized to develop a novel adaptive controller to estimate measurement bias and attempt to achieve consensus. The results show convergence of all agents to a neighborhood.

15:30 Afternoon Break

15:50 AAS 17-359 Spacecraft Forced Fly-around Formation Design and Control Based on Relative Orbit Elements

Ran Zhang, Beihang University; Chao Han, Beihang University; Qichen Zhao, Beihang University

In on-orbit servicing missions, fly-around technology is widely applied to keep the chasing spacecraft flying around the reference spacecraft at specified period.Flying-around formation is obtained by designing the chaser absolute orbit, and a set of relative orbit elements is introduced to describe the fly-around formation.Explicit geometric meaning makes it convenient to apply the fly-around formation in practical engineering problems.Moreover,based on relative orbit elements,an impulsive control strategy is proposed to complete the fly-around formation and reconfiguration.Numerical simulations are conducted to demonstrate the efficacy of these proposed methods.

16:10 AAS 17-383 Nonlinear Robust Control for Satellite Formation Flying via Adaptive Second-Order Sliding Modes

Hancheol Cho, University of Liege; Gaetan Kerschen, University of Liège

This paper presents a robust adaptive control methodology based on second-order sliding modes for satellite formation control in the presence of uncertainties. By introducing two sliding variables, a robust controller is designed so that it forces the first sliding variable to converge to a desired error box in a finite time. Then, the second sliding variable and the error are automatically bounded in a much smaller region. The proposed control scheme effectively alleviates chattering and a gain adaptive law is also presented. Numerical simulations are carried out to validate the efficiency and the accuracy of the proposed control scheme.

16:30 AAS 17-396 Geometric snapshot method for the autonomous relative positioning of formation flying satellites in real-time

Kathrin Frankl; Meltem Eren Copur, Universitaet der Bundeswehr; Bernd Eissfeller

The autonomous relative positioning of formation flying satellites is of major importance for a safe operation of the satellite formation. To this end, several challenges are faced: a stringent position accuracy requirement, the real-time capability of the positioning algorithm and the deviation of the measured satellite distances between some ranging system and the desired distances between the telescope reference points. In this work, these challenges are approached by developing two relative positioning algorithms that calculates the satellite positions based on pure geometric combinations of the measurements for each single time instant.

16:50 AAS 17-425 Adaptive fault-tolerant control for spacecraft formation flying while ensuring collision avoidance

Hongyang Dong, Harbin Institute of Technology; The University of Texas at Austin; Guangfu Ma, Harbin Institute of Technology; Yueyong Lyu, Harbin Institute of Technology; Maruthi Akella, The University of Texas at Austin

We address the target tracking and configuration maintaining problems for spacecraft formation flying systems, in which the fault-tolerant requirement of actuators and collision/obstacle avoidance ability are considered. Specifically, a potential function guidance scheme is designed in conjunction with a time-varying sliding manifold to enable the spacecraft formation can maintain the predetermined configuration while tracking a target, even though the existence of parametric uncertainties, disturbances, and severe actuator faults. In addition, benefits from the properties of the designed potential function, the proposed control method also guarantees the collision/obstacle avoidance ability of the formation with respect to all member spacecrafts and a non-cooperative obstacle.

17:10 AAS 17-450 Relative Satellite Navigation with Angles-LOS Measurements Using Relative Orbital Elements and Admissible Regions

Fouad Khoury, Purdue University; Alan Lovell, Air Force Research Laboratory

This paper investigates the computation and implementation of the relative constrained admissible region (RCAR) as a relative satellite motion navigation tool that collects angles only measurements from a reference spacecraft to perform initial relative orbit determination of a target space object in Earth orbit. This research addresses the need for a computationally inexpensive and accurate on-board space based navigation and orbit determination technique for use in future rendezvous, formation flight, and space-based observation missions. A preliminary design for a space based navigation/orbit determination algorithim involving relative admissible regions and ROEs will be formulated, assessed, and validated using simulations.

Feb 8, 2017Pavo Real

24 Guidance and Control

Co Chair: Sean Wagner

13:30 AAS 17-203 Cassini Spacecraft Attitude Control System: Flight Performance and Lessons Learned, 1997–2016

Allan Lee, Jet Propulsion Laboratory; Thomas Burk, Jet Propulsion Laboratory, California Institute of Technology

Since achieving orbit at Saturn in 2004, Cassini has collected science data throughout its four-year prime mission, and has since been approved for first and second extended missions through September 2017. Since its launch in 1997, the performance of the Cassini Attitude and Articulation Control Subsystem (AACS) design has been superb. All key mission and science requirements have been met with margins. However, in flight operations, new things were learned every day. The root causes of these “surprises” include flight and ground software errors, “pilot” errors, and other causes. Key lessons learned will be described in this paper.

13:50 AAS 17-223 USE OF MULTICOPTERS FOR LAUNCHERS PROBLEMATIC INVESTIGATIONS

Olivier BOISNEAU, CNES; Eric Bourgeois, CNES; Jean Desmariaux, CNES; David-Alexis Handschuh; Amaya Espinosa, CNES; Julien Franc, AERACCESS

Multicopters have many similarities with launchers for what concerns Guidance, Navigation and Flight Control. Their accessibility and their price make them ideal tools for launchers problematic investigations. A review of different domains has been perform to identify when multicopters will be or not representative of a launcher.

CNES launchers directorate initiated a project to use multicopter as test bench for launchers problematic investigations. The first application is to study, in flight, analogy between propellant sloshing and the equivalent pendulum models. A device has been design and a quadcopter has been used to prepare and demonstrate the feasibility of the concept.

14:10 AAS 17-227 Optimization method of installation orientation and baffle design for dual-FOVs star tracker

Geng Wang; Fei Xing; Minsong Wei; Ting Sun; Zheng You

Star tracker is an optical attitude sensor with high precision, and is susceptible to the stray light for the unreasonable installation orientation. In this work, an orientation method of dual- FOVs star tracker for sun-synchronous orbit was proposed based on a novel vector model of stray light, meanwhile, the orientation- vector of star tracker and corresponding shading- angle of sunlight and earthlight were optimized based on the boundary equations. The simulation results indicated that this method for installation orientation and baffle design of dual- FOVs star tracker was precise and effective, and can provide basis for the orientation of sun sensor simultaneously.

14:30 **AAS 17-342** **On Translational and Rotational Control of a Rigid Spacecraft in a Central Gravity Field with Only Attitude Control**

Christopher Petersen, University of Michigan; Frederick Leve, Air Force Office of Scientific Research; Ilya Kolmanovsky, University of Michigan

A set of coupled translational and rotational equations of motion for a spacecraft in a central gravity field is derived. The spacecraft is assumed to have only internal attitude actuators and the equations of motion are such that they are relative with respect to an equilibrium orbit. These equations are then approximated, and for certain orbits, yield dynamics similar to Hill-Clohessy-Wiltshire (HCW) dynamics. Under reasonable assumptions on the spacecraft configuration and equilibrium orbit, it is proven that the coupled dynamics are small-time locally controllable (STLC), which opens a path to utilizing conventional control techniques to move translationally in space

14:50 **AAS 17-296** **A New Steering Law for Variable Speed Control Moment Gyros**

Qingqing Dang, Beihang University; Lei Jin, Beihang University; Shijie Xu

A new steering law that calculate the frame angular velocity and the rotor angular acceleration separately is proposed for VSCMGs. The singularity index of VSCMGs is redefined and analyzed. When CMGs mode is close to singularity, the resulting torque error is compensated by RW mode. In order to avoid the rotor angular velocity difference is too large and make full use of the configuration redundancy, the null motion is introduced. The desired rotor angular velocity is given dynamically according to the angular momentum of the VSCMGs. Finally, validates the effectiveness of VSCMGs steering law is validated.

15:10 **AAS 17-339** **Initial Attitude Control Challenges for the Solar Probe Plus Spacecraft**

Robin Vaughan, JHU Applied Physics Laboratory; Daniel O'Shaughnessy, Johns Hopkins University Applied Physics Laboratory

The Solar Probe Plus (SPP) mission plans to launch a spacecraft to explore the Sun in 2018. Attitude control is maintained with a 3-axis stabilized, closed-loop control system. One of the first tasks for this system is acquiring attitude knowledge and establishing attitude control after separation from the launch vehicle. Once control is established, the spacecraft must be moved through a sequence of attitudes to meet power and thermal constraints and reach a power-positive state. This paper describes the options selected for the sequence of initial attitudes and gives results for expected performance for nominal and contingency timelines after separation.

15:30 **Afternoon Break**

15:50 **AAS 17-341** **Sun Direction Determination for the Solar Probe Plus Spacecraft**

Robin Vaughan, JHU Applied Physics Laboratory; John H. Wirzburger, The Johns Hopkins University Applied Physics Laboratory

This paper presents the process applied in the attitude control flight software for the SPP spacecraft to determine the best Sun direction from Sun sensor data or a vector derived from on-board ephemeris models and the estimated attitude. Self-consistency checks applied to determine validity of these different knowledge sources are explained, with emphasis on processing for solar limb sensor data. Consistency checks between the available data sources are described. The paper concludes with a presentation of the logical hierarchy that determines which source to select from among the available and valid sources and results of the consistency checks between them.

16:10 **AAS 17-420** **Near-Optimal Real-Time Spacecraft Guidance and Control Using Harmonic Potential Function**

Richard Zappulla, Naval Postgraduate School; Josep Virgili-Llop, Naval Postgraduate School; Marcello Romano, Naval Postgraduate School

In order to pursue advanced missions, improved on-board autonomous trajectory optimization and path (re-)planning are necessary.
Numerous missions over the past decade have pushed the state-of-the-art in autonomous rendezvous and proximity operations.
The primary requirement for any RPO guidance algorithm is obstacle avoidance, followed by fuel efficiency.
In this work, an innovative real-time hybrid guidance method fuses the flexibility and robustness of Harmonic Potential Functions with the asymptotically-optimal Rapidly-expanding Random Tree Star method.
Lastly, an experimental campaign is performed to quantify and validate the performance of this method utilizing the Naval Postgraduate School POSEIDYN test bed.

16:30 **AAS 17-424** **A Systematic Approach to Determining the Minimum Sampling Rate for Real-Time Spacecraft Control**

Richard Zappulla, Naval Postgraduate School; Marcello Romano, Naval Postgraduate School

Typical controller design and analysis methods utilize techniques for continuous-time systems. However, digital computation is the favored approach to implementing the resulting controllers. This leads to the natural question of choosing a sampling rate. There are several "Rules of Thumbs" for the choosing a sample rate derived from frequency domain properties of the system. A metric to estimate the sample rate based on time domain properties of the system is proposed. It is then validated via several case studies using representative mechanical systems, actuators, and controllers. Lastly, the paper concludes with a discussion on the applications of this metric.

16:50 AAS 17-436 LQ Attitude Control of a 2U Cubesat by Magnetic Actuation

Richard Sutherland, University of Michigan; Ilya Kolmanovsky, University of Michigan; Anouck Girard, University of Michigan

The paper describes the development of the attitude control subsystem for a 2U cubesat at the University of Michigan for participation in the QB50 Project. It details the development and simulation of an optimal control law using magnetic torque rods augmented with a set of aerodynamic drag panels. The equations of motion describing the satellite's attitude are derived in a body-fixed frame, incorporating the effects of gravity gradient torque. The continuous and discrete-time linear-quadratic controllers are simulated using the 2015 IGRF tilted dipole model of the Earth's magnetic field.

17:10 AAS 17-465 Receding Horizon Drift Counteraction and its Application to Spacecraft Attitude Control

Robert Zidek, University of Michigan; Ilya Kolmanovsky, University of Michigan; Christopher Petersen, University of Michigan; Alberto Bemporad, IMT Institute for Advanced Studies Lucca

A model predictive control (MPC) approach for drift counteraction optimal control (DCOC) is applied to attitude control of spacecraft with reaction wheels. The objective is to maximize the time that prescribed constraints on spacecraft orientation and reaction wheel spin rates are satisfied given external disturbance torques due to solar radiation pressure. While the MPC/DCOC approach is based on linear programming, all closed-loop simulations are performed using the nonlinear model. In case constraints are violated, a control strategy is presented that recovers constraint satisfaction (if possible). We consider the cases where either one, two, or three reaction wheels are operable.

17:30 AAS 17-491 Attitude Control of Spacecraft Formations subject to Distributed Communication Delays

Kamesh Subbarao, The University of Texas at Arlington; Siddharth Nair

This paper considers the problem of achieving attitude consensus in spacecraft formations with bounded, time-varying communication delays between spacecraft connected as specified by a strongly connected topology. A state feedback controller is proposed and a Linear Matrix Inequality (LMI) based approach is adopted to obtain a delay dependent stability criterion to achieve the desired consensus. Simulations are presented to demonstrate the application of the strategy in a specific scenario.

Feb 7, 2017La Villita C

25 Special Session: Interdisciplinary Challenges in Space Situational Awareness

Co Chair: Marcus Holzinger

Feb 9, 2017La Villita A

26 Trajectory Design and Optimization

Co Chair: Martin Ozimek

8:00 AAS 17-204 Validation of a Low-Thrust Mission Design Tool Using Operational Navigation Software

Jacob Englander, NASA Goddard Space Flight Center; Jeremy Knittel, NASA Goddard Space Flight Center; Kenneth Williams, KinetX Aerospace, Inc.; Dale Stanbridge, KinetX Aerospace, Inc.; Donald Ellison, University of Illinois at Urbana-Champaign Aerospace Engineering Department

Design of flight trajectories for missions employing solar electric propulsion requires a suitably high-fidelity design tool. In this work, the Evolutionary Mission Trajectory Generator (EMTG) is presented as a medium-high fidelity design tool that is suitable for mission proposals. \ac{EMTG} is validated against the high-heritage deep-space navigation tool MIRAGE, demonstrating both the accuracy of \ac{EMTG}'s model and an operational mission design and navigation procedure using both tools. The validation is performed using a benchmark mission to the Jupiter Trojans.

8:20 AAS 17-347 CUDA-Enhanced Integration for Quick Poincare Surface Intersections in a Global Optimization Framework for Low Energy Transfers

Joshua Aurich, University of Illinois at Urbana-Champaign; Ryne Beeson, University of Illinois at Urbana-Champaign; Victoria Coverstone, University of Illinois at Urbana-Champaign

Identifying homoclinic and heteroclinic intersections of manifolds associated with libration point periodic orbits has proven to be an effective design methodology for generating low-energy trajectory solutions in the restricted three-body problem. The method of intersection identification upon Poincaré surfaces of section has been previously automated by the authors; this paper extends that work by incorporating the algorithm into an automated global optimization framework. The second half of this paper then focuses on the important issue of making the automated detection process numerically efficient; otherwise run-time performance of the global optimizer could be excessive. We accomplish this by using graphics processing

8:40 AAS 17-368 A SOLUTION TO THE THREE-BODY LAMBERT PROBLEM BASED ON CUBATURE KALMAN FILTER PARAMETER ESTIMATION

Qichen Zhao, Beihang University; Hongli Zhang, Beihang University; Ran Zhang, Beihang University; Chao Han, Beihang University

The three-body Lambert problem is to find out an orbit determined from two position vectors and transfer time in the three-body system. Its solution is generally divided into two steps: initial guess based on the two-body model and final solution using cubature kalman filter parameter estimation (CPE). CPE is based on the theory of probability without the gradient matrixes which are hard to calculate. Moreover, by using CPE the demand for the accuracy of the initial values for the three-body Lambert problem is modified. Results show CPE is efficient, robust and has a larger convergence domain compared with other methods.

9:00 AAS 17-460 Optimal Coplanar Orbit Transfers in Levi Civita Coordinates

Marcelino Mendes de Almeida, The University of Texas at Austin; Maruthi Akella, The University of Texas at Austin

The objective of the present paper is to study optimal orbit transfers through Sequential Quadratic Programming techniques using Levi-Civita coordinates. The Levi-Civita coordinates is a useful orbit representation due to the fact that, for a body traveling through a trajectory with fixed semi-major axis, the equations of motion for these coordinates are represented by linear dynamics. We take advantage of the near-linear properties of this coordinate frame to quickly find optimal solutions for arbitrary planar orbit transfer.

9:20 AAS 17-479 Iterative Five-Element Lyapunov Control for Low Thrust Rendezvous with Modified Chebyshev Picard Iteration

Nathan Budd, Texas A&M University; Julie Read, Texas A&M University; Robyn Woollands, Texas A&M University ; John Junkins, Texas A&M University

We present an iterative five-element Lyapunov control for low thrust rendezvous that uses Modified Chebyshev Picard Iteration (MCPI), an iterative solver of linear and nonlinear ordinary differential equations (ODE). MCPI uses Chebyshev polynomials to approximate the orbital trajectory and then uses Picard iteration to improve the approximation iteratively. We discuss simulations of two rendezvous test cases, which illustrate the effectiveness of this method as a computationally cheap alternative to relatively expensive optimal control solutions.

9:40 AAS 17-480 ACTIVE VIBRATION CONTROL OF GYROELASTIC BODY WITH OPTIMAL PLACEMENT OF ACTUATORS
Shiyuan Jia; Yinghong Jia; Shijie Xu

In this study, we present the optimal placement of actuators for the gyroelastic body by using the linear quadratic regulator (LQR) performance. Genetic algorithm is used to solve the combinatorial problems of the optimal placement. The optimal placement of actuators under different installation directions is discussed. The results of the optimal placement show that the CMGs are located at the locations with bigger slopes of flexible modes. The LQR optimal control scheme is applied to study the control effectiveness based on the optimized configuration. The control effectiveness of actuators with hybrid installation directions is better than the other situations with the same directions

10:00 Morning Break

10:20 AAS 17-487 Trajectory and navigation design for an impactor mission concept
Andres Dono Perez; Roland Burton; David Mauro; Jan Stupl

This paper introduces a trajectory design for a secondary spacecraft concept to augment the science return in interplanetary missions. The concept consists of a single-string probe with a kinetic impactor on board that generates an artificial plume to perform in-situ sampling. A Monte Carlo simulation was used to validate the nominal trajectory design for a particular case study that samples ejecta particles from the Jupiter's moon Europa. Details regarding the navigation, targeting, and disposal challenges related to this concept are presented herein.

10:40 AAS 17-502 COOPERATIVE GUIDANCE WITH IMPACT ANGLE CONSTRAINT BASED ON LEADER-FOLLOWER STRATEGY

Teng Lyu; Yueyong Lyu; Chuanjiang Li

A new time-cooperative guidance law against a stationary target is proposed in this paper, which can be applied to salvo attack of anti-ship missiles with the impact angle constraint. Firstly, the nonlinear motion equations of missiles are linearized and various constraints are formulated. Secondly, centralized leader-follower topology based guidance laws of the leader and followers are presented. Finally, closed-form trajectory solutions are given to demonstrate that the zero miss distance and desired impact angle performance of all the missiles can be achieved. Simulation results demonstrate the effectiveness of the proposed guidance law.

11:00 AAS 17-528 THE USE OF LUNI-SOLAR GRAVITY ASSISTS FOR ASTEROID RETRIEVAL

Hongru Chen, Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences

Luni-solar gravity assists is proposed for asteroid retrieval. The trajectory design is to find the sequence of Sun-perturbed Moon-Moon transfers and lunar swingbys to reduce the v_∞ with respect to the Moon to a low level, so that the asteroid can be inserted to a lunar orbit with little effort. However, it is burdensome to compute optimal heliocentric transfer and capture trajectories for every asteroid. This paper presents analyses revealing the capture capacity of luni-solar gravity assists. Then, asteroid candidates can be easily selected out. There are 13 asteroids that can be retrieved during the period from 2020 to 2030.

11:20 AAS 17-524 Orbit Manipulation by use of Lunar Swing-by on a Hyperbolic Trajectory

Shuntaro Suda, Hokkaido university; Yasuhiro Kawakatsu, JAXA / ISAS

In the modern space development, small-scale deep space mission should be realized to promote frequent and challenging deep space mission. Therefore, the efficient and quick design method to construct Earth escape trajectory with high flexibility in the boundary condition such as escape velocity, direction and timing is strongly demanded. In this paper, the families of Moon-to-Moon transfers with sequential lunar swing-by on a hyperbolic orbit are computed and stored in a database. These families are useful to enhance the Earth escape energy and to change escape direction which could lead a spacecraft to further destinations.

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27 Orbital Dynamics II

Co Chair: Daniel Lubey

8:00 AAS 17-226 Orbit Transfer of an Earth Orbiting Solar Sail Cubesat

Omer Atas, Middle East Technical University, Aerospace Engineering Department; Ozan Tekinalp, METU Aerospace Engineering Dept.

Propelling a spacecraft by using solar radiation pressure is examined in the context of orbital maneuvers. A locally optimal steering law to progressively change number of selected orbital elements together is addressed. An Earth centered cubesat satellite with solar sail is used as an example. The proper attitude maneuver mechanization is proposed to harvest highest solar radiation force in the desired direction for such Earth orbiting satellites. The satellite attitude control is realized using to-go quaternion feedback control. The effectiveness of the approach to progressively changing the orbital parameters is demonstrated.

8:20 AAS 17-352 An analysis of the convergence Newton's iterations for solving elliptic Kepler's equation

Manuel Calvo, Universidad de Zaragoza; Antonio Elipe, Centro Universitario de la Defensa. Zaragoza; Juan I. Montijano, Universidad de Zaragoza; Luis Randez, Universidad de Zaragoza

Numerical solution of Kepler's Equation (KE) has been a continuous subject of research for several centuries. When it is necessary to solve it thousands or millions times, to have good starters and fast convergence is of capital importance. Newton's iteration method has been widely used to solve KE. Recently, by using Smale's α-test on the convergence of Newton's iteration have been obtained a starter that guarantees super-convergence with rate $q=1/2$ for all values of the eccentricity $e\in[0,1)$ and mean anomaly and even super-convergence with rate $q\in (0,1)$ by using the classical Newton-Kantorovich theorem on convergence. Here we extend our previous

8:40 AAS 17-389 ORBITAL MANEUVERS IN THE NON-CENTRAL GRAVITATIONAL FIELD OF PHOBOS PERTURBED BY THE GRAVITATIONAL ATTRACTION DUE TO MARS, SUN AND DEIMOS

Liana Gonçalves; Evandro Rocco; Rodolpho Moraes, UNIFESP

The fact that Phobos orbits so close to its primary added to the considerable difference of mass between Phobos and Mars, makes it even more difficult to maintain a trajectory around Phobos for a long period of time. This work aims at contributing to the assessment of possibilities of maneuvers to transfer a satellite from an orbit close to the Mars surface to an orbit close to the Phobos surface, also the search for trajectories in Phobos vicinity, as well as to maneuver the vehicle in order to bring it closer to the surface of that moon.

9:00 AAS 17-394 INVESTIGATION OF CRITICAL INCLINATION AND SUN-SYNCHRONOUS ORBITS AROUND THE MOONS OF SATURN

Liana Gonçalves; Maria Lívia da Costa; Rodolpho Moraes, UNIFESP; Evandro Rocco

This study aims the investigation of possible orbits with critical inclination and low sun-synchronous orbits around the nine largest moons of Saturn. This analysis is based on the gravitational potential of the moon, whose non-uniform mass distribution is described by oblateness J2 and by the equatorial ellipticity C22. Simulations are performed for spacecraft maneuvers approaching these natural satellites, according to some of the orbits found on the first step. These simulations consider the perturbation effects due to the gravitational potential of Saturn, the gravitational attraction of the Sun, the non-uniform distribution of the moons mass and the solar radiation pressure.

9:20 AAS 17-398 Decoupled Direct State Transition Matrix Calculation with Runge-Kutta Methods

Noble Hatten, The University of Texas at Austin; Ryan Russell, The University of Texas at Austin

Many optimization and estimation algorithms require the sensitivities of a dynamic system. In this paper, the decoupled direct method is derived for the calculation of first- and second-order state transition matrices (STMs) using either the single- or double-integrator form of a Runge-Kutta (RK) ordinary differential equation solver. Implications for explicit and implicit RK methods are discussed. For implicit solvers, the decoupling of the state propagation and STM calculation can create significant computational savings compared to the propagation of the variational equations, particularly for systems with expensive dynamics. The effects of implicit RK customizations are also examined.

9:40 AAS 17-409 Expansion of the gravitational potential of a polyhedral body in inertial integrals

Stefano Casotto, Universita' di Padova; Roberto Casotto, University of Padua

A new method to compute the gravitational potential at field points outside the Brillouin sphere of a constant density, irregular body defined by a triangular surface mesh is presented. It is based on an expansion in Cartesian coordinates and makes us of the inertial integrals introduced by MacMillan in 1930. The novelty of the method is that a fully analytical formulation is developed for the computation of the inertial integrals to any degree by simple evaluations of line integrals based on the coordinates of the mesh points through the use of Bernstein polynomials.

10:00 **Morning Break**

10:20 **AAS 17-435** **Stability regions in the N-Body problem: the Distant Retrograde Orbits family case**

Antonio Maria Pafundi; Michèle Lavagna, Politecnico di Milano

The paper discusses the long term stability of the Distant Retrograde Orbits, currently under consideration for the NASA Asteroid Redirect Robotic Mission (ARRM). The chaotic indicator MEGNO is here adopted and the confirmation on the stability near the third order resonance is investigated.

The study is then extended to the full *N*-body problem including all the major perturbations in the solar system. A progressive reduction in the stability region of the family is identified. The coupled orbital-attitude stability assessment – performed adopting an ellipsoidal model for the asteroid- is also presented.

10:40 **AAS 17-463** **A COMPARATIVE STUDY OF DISPLACED NON-KEPLERIAN ORBITS WITH IMPULSIVE AND CONTINUOUS THRUST**

Jules Simo, University of Central Lancashire

A study of novel families of highly non-Keplerian orbits (NKO) for spacecraft utilising either solar sail or solar electric propulsion (SEP) at linear order are investigated in the circular restricted three-body problem (CRTBP). In addition to a detailed investigation of the dynamics and control of highly NKO, effort will be devoted to develop a strategy that uses maneuvers executed impulsively at discrete time intervals. Thus, impulse control is investigated as a means of generating displaced orbits. In order to compare the continuous thrust and impulse control orbits, linearised equations of motion will be considered for small displacements.

11:00 **AAS 17-472** **Development of an Analytic Expression for Estimating the Time When the Uncertainty Becomes Non-Gaussian**

Inkwan Park, Texas A&M University; Kyle T. Alfriend, Texas A&M University

The objective of this research is to develop an analytic method for estimating the time when the uncertainty becomes non-Gaussian for specific initial conditions. The method is based on an extended Mahalanobis distance, that includes the nonlinear effects of the dynamics of the 2-dimensional semi-major axis - mean-anomaly space for Keplerian motion. It is hypothesized that there exists a specific ratio of the cumulative probability densities of the linear and nonlinear propagated uncertainties that determines when the uncertainty becomes non-Gaussian. Then based on this hypothesis an analytic method is derived to determine when the uncertainty becomes non-Gaussian.

11:20 AAS 17-473 Exact Normalization of the Tesseral Harmonics

Bharat Mahajan, Texas A&M University; Srinivas R. Vadali, Texas A&M University; Kyle T. Alfriend, Texas A&M University

A new analytic solution for performing an exact Delaunay normalization of the tesseral and sectorial harmonics is presented. The generating function for eliminating the short period variations from the osculating elements is computed without resorting to series expansions in the eccentricity. As a result, the satellite analytic theories constructed using the proposed approach are also valid for moderate to high values of eccentricity. The proposed method produces a significantly compact and unified satellite theory valid for subsynchronous and supersynchronous orbits unlike the iterative relegation method. Additionally, no singularities exist in the proposed solution for resonant orbits.

11:40 AAS 17-355 Long-term Analytical Propagation of Satellite Relative Motion in Perturbed Orbits

Tommaso Guffanti, Stanford University; Simone D'Amico, Stanford University; Michèle Lavagna, Politecnico di Milano

This work aims to provide new linear dynamic models for the propagation of satellite relative motion including perturbations as Solar Radiation Pressure (S.R.P.), Sun/Moon third body and geopotential J_3component. In particular, three new plant matrices that link the quasi-nonsingular Relative Orbital Elements (ROE) state with its time derivative, modeling the considered perturbing effects in orbits of arbitrary eccentricity, are obtained. These linear dynamic models are validated and their propagation performances are assessed with respect to a high accurate numerical propagator. Finally, a physical interpretation of S.R.P and third body effects on the ROE is provided.

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28 Orbit Determination

Co Chair: Cameron Meek

8:00 **AAS** **Variable Expansion Points for Series Solutions of the Lambert Problem**
17-236 *James Thorne, IDA; Dennis DeRiggi, IDA*

Lambert's problem of initial orbit determination is represented by a set of transcendental equations due to Lagrange. Power series solutions have been previously published that reverse the Lagrange equations to provide direct expressions for the unknown semi-major axis as an explicit function of the input transfer time. In this paper, convergence of the series solutions is achieved for certain problematic cases through the introduction of variable expansion points as a simple function of the input parameters. The resulting series expression for the transfer time may be reversed to produce convergent series solutions for the unknown semi-major axis over the full domain of interest.

8:20 **AAS** **Least-Squares Solutions of Linear Differential Equations**
17-256 *Daniele Mortari, Texas A&M University*

This study shows how to obtain least-squares solutions to initial and boundary value problems to nonhomogeneous linear differential equations with nonconstant coefficients of any order. The method write the solution with embedded constraints. These constrained expressions are written in terms of a new generic function, g (t), and in a such a way to satisfy the constraints, no matter what g(t) is.The proposed method is applied to solve initial, boundary, and mixed value problems. Numerical tests are provided to quantify the solution accuracy obtained for second order differential equations with known solution, unknown solution, no solution, and infinite solutions.

8:40 **AAS** **Solving the Kepler equation with the SDG-code**
17-361 *Virginia Raposo-Pulido; Jesus Pelaez, Technical University of Madrid (UPM)*

A new code to solve the Kepler equation for elliptic and hyperbolic orbits has been developed. The motivation of the study is the determination of an appropriate seed to initialize the numerical method, considering the optimization already tested of the well known Newton-Raphson method. To do that, we take advantage of the full potential of the symbolic manipulators. The final algorithm is stable, reliable and solves successfully the solution of the Kepler equation in the singular corner ($M<<1$ and $e \sim 1$)

9:00 **AAS 17-304** **On the resolution of the Lambert's problem with the SDG-code**

Virginia Raposo-Pulido; Jesus Pelaez, Technical University of Madrid (UPM)

Based on the Lambert's problem, once identified the one-parameter family of orbits that verify the geometric constraints of the problem, we must express the orbits based on a single parameter that allows to select those that satisfy the kinematic condition. The aim of this paper is to reformulate the problem choosing as parameter the true anomaly of the bisector defined by the directions of the two position vectors. The algorithm applied is the SDG-code, developed by the Space Dynamics Group at UPM, which has already been assessed on the resolution of the Kepler equation proving its stability and reliability.

9:20 **AAS 17-408** **Wide Field-of-View Time Differencing Orbit Determination**

Nicholas Bijnens, York University; Franz Newland, York University; Jinjun Shan, York University

With today's significant increase of interest in nanosatellite development, as well as the update frequency of the NORAD TLE data, the options for satellite orbit determination are often slim. The method proposed in this paper will allow a satellite to use its own payload data to determine its orbital elements at any time instant, without the need for additional on-board equipment or processing. To-date, using a custom modified SPSA algorithm has proven the concept to be viable, where each of the six orbital elements was estimated to within one percent of their true value at an arbitrary time instant.

9:40 **AAS 17-421** **HIGHER-ORDER DIFFERENTIAL CORRECTION SOLVER FOR PERTURBED LAMBERT PROBLEM**

Mohammad Alhulayil, Khalifa University; Ahmad Bani Younes, Khalifa University, Abu Dhabi; James Turner, Khalifa University, Abu Dhabi

This paper presents an extension of the classical 1st order shooting solver for lambert's problem to 4th order differential correction. The resulting Taylor expansion model requires 1st through 4th order state transition tensors (STTs) that relate the sensitivity of the terminal position errors with respect to the initial velocity vector. These STTs are generated using Computational differentiation (CD) tool integrated with high-order differential correction solver for lambert problem. The two body motion is perturbed using 200x200 spherical harmonic gravity model.

10:00 **Morning Break**

10:20 AAS 17-430 A Splitting Gaussian Mixture Formulation for a Nonlinear Measurement Update

Kirsten Tuggle; Renato Zanetti, The University of Texas at Austin; Christopher D'Souza, NASA - Johnson Space Center

Applications such as orbit determination and ground tracking necessitate accurate knowledge of state estimate uncertainty. Adaptive Gaussian mixture models are a favored approach with much work devoted to the prediction phase. Of the fewer splitting schemes provided for the filtering phase, nearly all choose to split components along the direction of maximum prior uncertainty. While this does address the goal of reducing uncertainty, it does not consider the role of the actual nonlinear measurement function. The proposed method offers a novel filtering step splitting scheme that addresses both contributors in a more computationally efficient manner than much of the literature.

10:40 AAS 17-235 Optimal k-vector to Invert Nonlinear Functions

David Arnas, Centro Universitario de la Defensa - Zaragoza; Daniele Mortari, Texas A&M University

This work proposes a numerical technique to perform extensive inversions of one dimensional explicit nonlinear functions within assigned ranges of interest. The approach proposed, which is based on the k-vector range searching technique, is suitable when extensive inversions of the same function must be done. The method inverts the function with machine error precision and it is extremely fast. However, it requires a pre-processing computation done, just once, for each function of interest. This method can be also applied to provide inversion estimates of tabulated data of unknown functions. Numerical examples are provided for some nonlinear analytic and tabulated functions.

11:00 AAS 17-297 Random Number Generation using k-vector

David Arnas, Centro Universitario de la Defensa - Zaragoza; Daniele Mortari, Texas A&M University

This work focuses on random number generation following a probability density function using the k-vector methodology. The k-vector is a numerical technique devised for fast range searching on large databases at a computational cost independent on the size of the database. We introduce two approaches. The first is based on inverse transform sampling using an optimal k-vector to generate the numbers by the inversion of the cumulative distribution. The second generates samples using random searching in a pre-generated large database built by massive inversion of the probability density function using the k-vector.

Feb 9, 2017Pavo Real

29 Attitude Dynamics and Control III

Co Chair: Manoranjan Majji

8:00 **AAS 17-428** **Precision Attitude Stabilization: Inputs Scaled by Persistently Exciting Diagonal Matrices**

Hongyang Dong, Harbin Institute of Technology; The University of Texas at Austin; Maruthi Akella, The University of Texas at Austin

A certain type of spacecraft attitude stabilization problem is addressed, in which the control inputs are scaled by time-varying, singular gains in the form of a diagonal matrix. And these control scaling gains are supposed to satisfy persistency of excitation conditions. Based on a novel state-dependent filter, a feedback control method is proposed to achieve the precision stabilization objective. A salient feature of this result is that the states of the closed-loop system are shown satisfy exponential convergence properties. As an interesting practical application, a special attitude stabilization problem for spacecraft with just a single, gimbaling-based thruster is studied.

8:20 **AAS 17-446** **NONLINEAR ATTITUDE DYNAMICS OF A RIGID BODY AT THE LAGRANGIAN POINTS**

Lorenzo Bucci, Politecnico di Milano; Michèle Lavagna, Politecnico di Milano

The research discusses the analytical solution for the planar attitude dynamics of a rigid body, located at an equilibrium point of the Circular Restricted Three-Body Problem. The dynamics equations are compared to the nonlinear dynamics of a swinging pendulum, for which literature offers the exact solution; such solution is thus adapted and employed for the case at hand. Three-dimensional attitude stability of the rotating body is investigated, both for oscillations (no net swing over) and for multiple swings, providing novel results and stability charts. Eventually, three-dimensional periodic attitude solutions are presented and analyzed.

8:40 **AAS 17-451** **Volume Multi-Sphere-Model Development Using Electric Field Matching**

Gabriel Ingram, University of Colorado; Joseph Hughes; Trevor Bennett, University of Colorado; Hanspeter Schaub, University of Colorado; Christine Reilly

The Volume Multi-Sphere Method (VMSM) seeks the optimal placement and radii of a small number of equipotential spheres to accurately model the electrostatic interaction between a command and target object at a variety of relative positions. A drawback of current VMSM methodologies is that the optimal model is produced as a result of fitting to force and torque produced by finite element analysis software, requiring appropriate probe geometry and significant amounts of time. A novel VMSM fitting technique based on analytically produced electric fields is proposed which eleminates model dependence on probe geometry and significantly increases the speed of model generation.

9:00 AAS 17-458 On the Robust Attitude Regulation for Earth Observation Spacecraft Under Hybrid Actuation

Dimitrios Pylorof, The University of Texas at Austin; Srinivas Bettadpur, University of Texas at Austin/Center for Space Research; Efstathios Bakolas, The University of Texas at Austin

Mission requirements for Earth observation spacecraft often influence the design philosophy of the latter and may additionally impose constraints and performance objectives on their attitude control functionality. We study the robust attitude regulation problem for such spacecraft, characterized primarily by hybrid actuation consisting of magnetic actuators and thrusters, assuming noisy attitude feedback. In our problem formulation, the angular accelerations induced by the attitude stabilization have to remain sufficiently small due to payload requirements. A linear robust control law is developed, which is tailored to the hybrid actuation scheme by appropriately complementing the directionally constrained magnetic torque with the thrusters.

9:20 AAS 17-468 A SIMPLIFIED MODEL FOR VIBRATING MASS CONTROL MOMENT GYROSCOPE

Burak Akbulut, Turkish Aerospace Industries Inc.; Ozan Tekinalp, METU Aerospace Engineering Dept.; Kıvanç Azgın, METU Mechanical Engineering Dept.; Ferhat Arberkli, METU Mechanical Engineering Dept.

A novel satellite attitude actuator based on vibrating masses had been previously proposed. Moreover, its governing equations were obtained and simulated utilizing MATLAB/SIMULINK environment. The mathematical model obtained in this manner turned out to be cumbersome due to its involvement of extensive matrix calculations. In this work, a representative simplified set of equations are obtained describing vibrating mass control moment gyroscope (vCMG) dynamics in high fidelity. This simplified mathematical model is then validated via energy methods and simulations in MATLAB/SIMULINK. It was found that the simplified model posed adequate substitute for the representation of complex vCMG dynamics under certain conditions.

9:40 AAS 17-478 Real-time Attitude Control for Large-angle Agile Maneuvers of a Spacecraft with Control Moment Gyros

Shota Kawajiri, Tokyo Institute of Technology; Saburo Matunaga

Control moment gyro system is a promising actuators for missions requiring agile maneuverings. Taking advantage of the nature of existing a coasting period in a time-optimal maneuver, we developed a real-time path planning method under mechanical constraints for an agile large-angle maneuver using control moment gyros. Numerical simulations are carried out to verify the validity and effectiveness of the proposed method. The results show that our method can shorten the settling time by 20-70% compared with typical feedback control and can be carried out 150 times as fast as a previous agile maneuvering method can.

10:00 Morning Break

10:20 AAS 17-490 Design and Validation of Hybrid Attitude Determination and Control System for CubeSat through Hardware-in-the-Loop Simulation

Dae Young Lee, Center for Space Research, University of Texas at Austin; Hyeongjun Park, Naval Postgraduate School; Marcello Romano, Naval Postgraduate School; James Cutler, University of Michigan

In this paper, the design and experimental validation process for CubeSat attitude determination control system (ADCS) is introduced. To test and verify an ADCS realistic simulation environment is required. Using a physical test bed based on a hemispheric air bearing, a hardware-in-the-loop simulation (HILS) is implemented for ground testing of an ADCS algorithm. From several tests on HILS, the control algorithms are analyzed and compared for attitude tracking. In addition, the switching condition for attitude estimation algorithms is verified. Based on these test results, the design of multi-algorithmic Hybrid ADCS is modified and finalized.

10:40 AAS 17-493 Optimal Attitude Determination and Control System design for LAICE and CubeSail

- Vedant, University of Illinois at Urbana Champaign; Erik Kroeker, University of Illinois at Urbana-Champaign; Alexander Ghosh, University of Illinois at Urbana-Champaign

This study discusses the optimal design of Attitude Determination and Control System

(ADCS), for CubeSail and LAICE missions based on the IlliniSat-2 bus. CubeSim, a Hardware-In the-Loop(HIL) simulation platform is utilized for designing and verifying the ADCS. A novel approach of optimizing the determination and control system collectively with respect to the system's power requirements, is presented. The power requirements are considered by including a battery charge and discharge model, and the impact of orbital position and attitude. The optimized ADCS with the battery model are the validated for the mission in a HIL test, and the results are discussed.

11:00 AAS 17-497 Extending software capabilities of CubeSim: a hardware in the loop simulation package

- Vedant, University of Illinois at Urbana Champaign; Erik Kroeker, University of Illinois at Urbana-Champaign; Alexander Ghosh, University of Illinois at Urbana-Champaign

CubeSim is a Hardware-In-the-Loop (HIL) simulation for the calibration and validation of Attitude Determination and Control system of IlliniSat-2 CubeSat bus. This study introduces two main modifications to the CubeSim software package improving simulation accuracy.

First, the calibration algorithm for the Helmholtz Cage (HC3) is optimized to produce a more uniform magnetic field in the test region, allowing simultaneous calibration of flight magnetometers. Second, the accuracy of magnetic model for HC3 is augmented using the Enhanced Magnetic Model, yielding a more realistic model.

11:20 AAS 17-500 Finite-time Passivity Based Controller with Higher-order Observer for Space Multibody Robots

Li Jinyue, Beijing Institute of Technology; Quan Hu; Jingrui Zhang

Most of existing multibody systems control approaches are asymptotically stable, which implies system`s trajectories converge to the origin as time goes to infinity. To obtain faster convergence rate and higher performance, finite-time stability are proposed and applied to multibody systems. It is also noticed that multibody systems can be passive with appropriate actuators and sensors. So many passivity based multibody system control laws have been suggested, but most of them are asymptotically stable. In this work, finite-time control and passivity based control are combined together, so that finite-time passivity approach with strong robustness is developed. A higher-order sliding mode observer is incorporated to compensate modeling uncertainties and disturbance.

11:40 AAS 17-507 EFFECT OF SUN SHADE PERFORMANCE ON ICESAT-2 LASER REFERENCE SENSOR ALIGNMENT ESTIMATION

Chirag Patel, University of Texas at Austin; Noah Smith, Voipfuture GmbH; Sungkoo Bae; Bob Schutz, University of Texas at Austin

Laser pointing knowledge for the remote sensing ICESat-2 is obtained from the laser reference sensor (LRS), which observes stars and altimeter measurements. The LRS is modeled by two functions of the angle between star tracker zenith and the sun: alignment relative to the spacecraft; and sensitivity, or magnitude of the dimmest trackable star. The objective is to track sun-driven motion using star observations degraded by the sun. Sunshade performance determines the change in sensitivity between sunrise and full blinding. Effects of several sensitivities and sun shades on laser pointing knowledge (and consequently geolocation of the laser spot) are characterized.

12:00 AAS 17-485 NON LINEAR K-VECTOR

Marcio A. A. Fialho, INPE - Instituto Nacional de Pesquisas Espaciais; Daniele Mortari, Texas A&M University; Leonel Perondi

The k-vector search technique is a general purpose search method that is capable of locating entries in a sorted array much faster than competing alternatives such as the binary search technique. It is based on an *m*-long vector of integers, called the k-vector. The traditional k-vector performs best when the values in the sorted array are uniformly distributed. In this paper we extend the k-vector technique by the use of non-linear mapping functions, and show how this approach can solve performance and memory limitations of the traditional k-vector for searches in arrays with strongly non-uniform distributions of values.