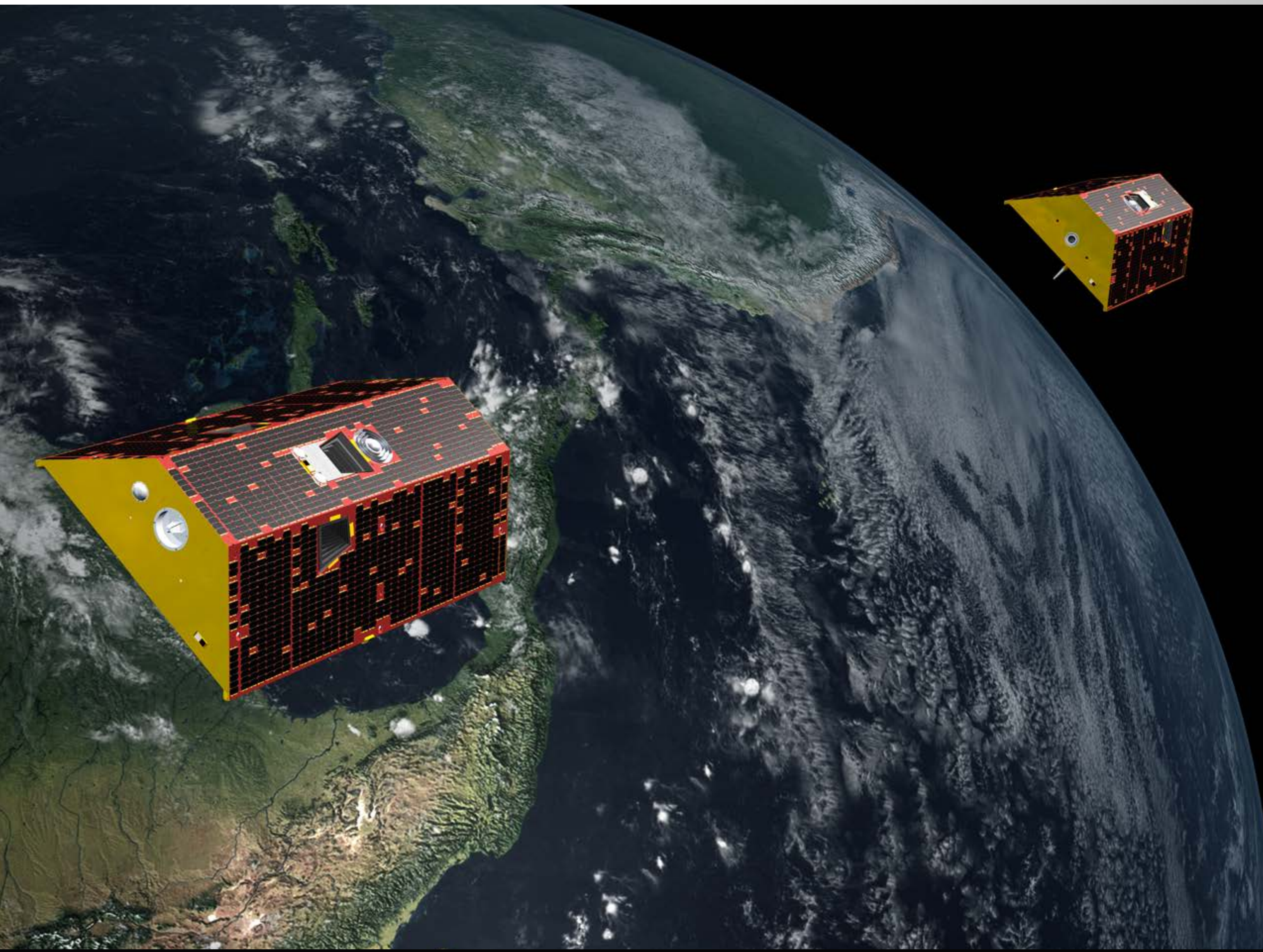
# 2018 AAS/AIAA Astrodynamics Specialist Conference

## August 19-23
## Snowbird, UT



*AAS General Chair*
**Dr. Belinda Marchand**
**Progalaxia, LLC**

*AIAA General Chair*
**Dr. Brandon A. Jones**
**The University of Texas at Austin**

*AAS Technical Chair*
**Dr. Puneet Singla**
**The Pennsylvania State University**

*AIAA Technical Chair*
**Dr. Ryan Weisman**
**Air Force Research Laboratory**

***08/15/2018***

# 2018 AAS/AIAA ASTRODYNAMICS SPECIALIST CONFERENCE

# CONFERENCE INFORMATION

## GENERAL INFORMATION

Welcome to the 2018 Astrodynamics Specialist Conference, hosted by the American Astronautical Society (AAS) and co-hosted by the American Institute of Aeronautics and Astronautics (AIAA), August 19 – 23, 2018. This meeting is organized by the AAS Space Flight Mechanics Committee and the AIAA Astrodynamics Technical Committee, and held at The Cliff Lodge, 9320 Cliff Lodge Dr., Snowbird, UT 84092, (801)-933-2222, https://www.snowbird.com/lodging/the-cliff-lodge/.

## REGISTRATION

***Registration Site (https://www.xcdsystem.com/aas/attendee/index.cfm?ID=cQgRz2U)***

In order to encourage early registration, we have implemented the following conference registration rate structure: **Register by June 30, 2018 and save $70!**

| Category | Early Registration (through Jun 30, 2018) | Registration (beginning Jul 1, 2018) | Walk-up Registration (beginning Jul 26, 2018) |
|---|---|---|---|
| Full - AAS or AIAA Member | $590 | $660 | $760 |
| Full - Non-member | $690 | $695 | $795 |
| Retired (Member) or Student* | $200 | $270 | $370 |
| Retired - Non-member | $300 | $370 | $470 |

**does not include proceedings CD*

Refunds will be issued in full until July 24, 2018. A 10% fee will be assessed for all refunds issued after that date and until 8:00 am PST August 18, 2018. No refunds will be issued after 8:00 am PST August 18, 2018.

One ticket to The Summit at Snowbird on Tuesday evening is included with every registration. This includes dinner at the top of the mountain and the tram. Guest tickets for the event may be purchased for $70 per person. More information about the offsite event 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 Front Desk Lobby of the Cliff Lodge and will be staffed according to the following schedule:

- Sunday August 19: 3pm – 6pm
- Monday August 20: 7:30am – 2pm
- Tuesday August 21: 8am – 2pm
- Wednesday August 22: 8am – 2pm
- Thursday August 23: 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.**"

Credit: Cover image of the GRACE Follow-On mission is courtesy of NASA.

## SCHEDULE OF EVENTS

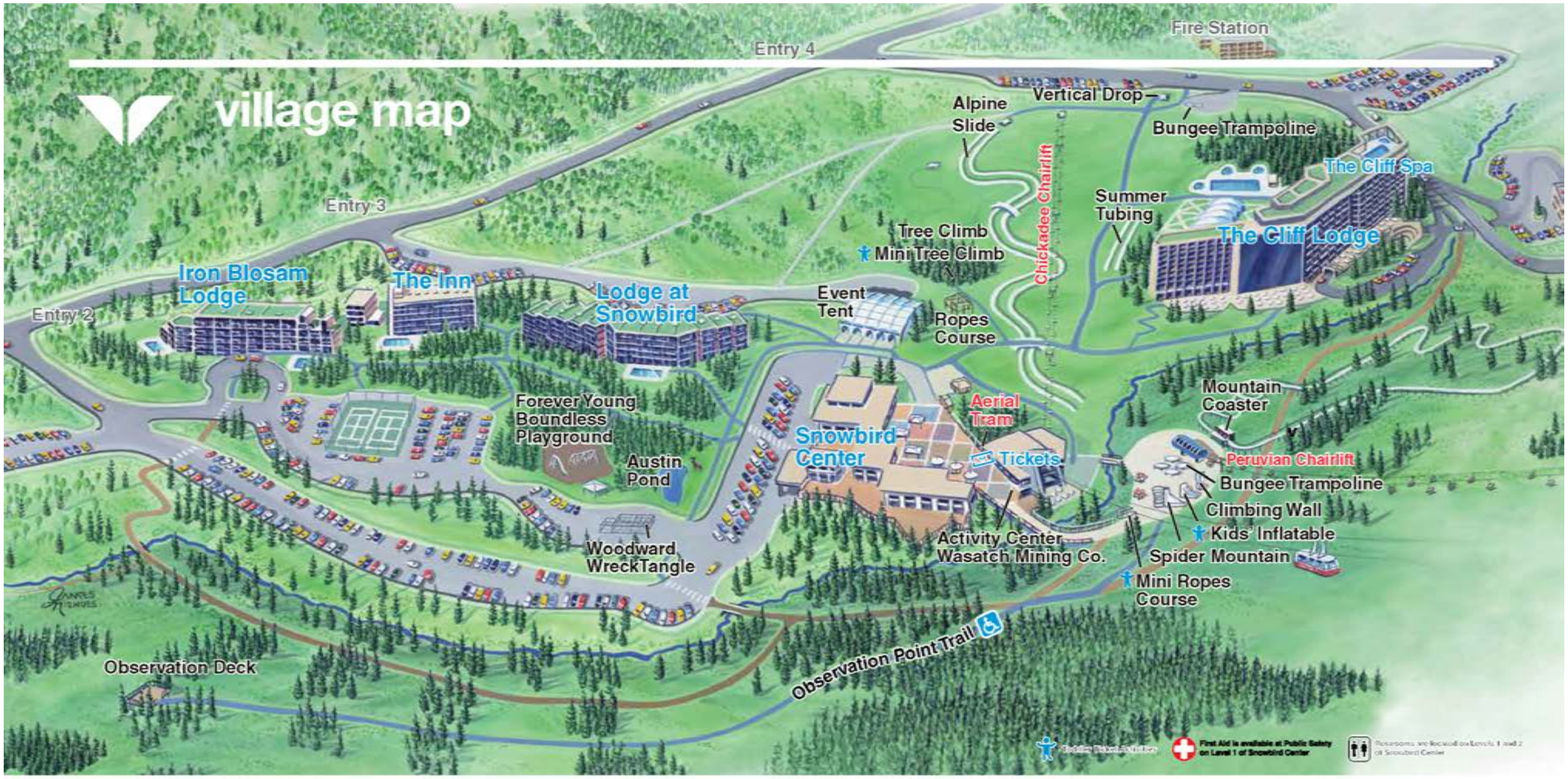
Technical sessions begin on Monday, 20 August, at 8 am. The last technical sessions end at 12:20 pm on Thursday, 23 August. Presentations are limited to 15 minutes with an additional 5 minutes for questions and answers. Each session has a 20-minute morning or afternoon break. Authors are required to 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 19 August*** | 3pm | 6pm | Registration | Front Desk Lobby |
| | 6pm | 9pm | Early Bird Reception (Food and Hosted Bar) | Conference Center Terrace |
| ***Monday 20 August*** | 7:30am | 2pm | Registration | Front Desk Lobby |
| | 8am | 12pm | Session 1: Astrodynamics I | Superior A |
| | 8am | 12pm | Session 2: Prox. Missions and Formation Flying I | Superior B |
| | 8am | 12pm | Session 3: Trajectory Design and Opt. I | Maybird |
| | 8am | 12pm | Session 4: Space Situational Awareness I | Cirque |
| | 9:40am | 10:00am | Morning Break | Superior Lobby |
| | Noon | 1:30pm | Joint Technical Committee Lunch | Aerie Private Dining Room |
| | 1:30pm | 5:30pm | Session 5: Attitude Dynamics & Control I | Superior B |
| | 1:30pm | 5:30pm | Session 6: Spacecraft GNC I | Superior A |
| | 1:30pm | 5:30pm | Session 7: Asteroid & Non-Earth Orb. Missions I | Maybird |
| | 1:30pm | 5:30pm | Session 8: Orbital Debris | Cirque |
| | 3:10pm | 3:30pm | Afternoon Break | Superior Lobby |
| | 5:30pm | 6:30pm | Cocktail Reception | Conference Center Terrace |
| | 6:30pm | 8:30pm | Dirk Brouwer Award Plenary and Breakwell Student Travel Award Presentation | Ballroom 1 |

| Day | Start | End | Function | Room |
| --- | --- | --- | --- | --- |
| ***Tuesday 21 August*** | 8am | 2pm | Registration | Lobby |
| | 8am | 12pm | Session 9: Astrodynamics II | Superior A |
| | 8am | 12pm | Session 10: Trajectory Design and Optimization II | Maybird |
| | 8am | 12pm | Session 11: Attitude Dynamics & Control II | Superior B |
| | 8am | 12pm | Session 12: Space Situational Awareness II | Cirque |
| | 9:40am | 10:00am | Morning Break | Superior Lobby |
| | Noon | 1:30pm | AIAA Technical Committee Lunch | Aerie Private Dining Room |
| | 1:30pm | 5:30pm | Session 13: Prox. Missions and Formation Flying II | Superior B |
| | 1:30pm | 5:30pm | Session 14: Orbit Determination | Superior A |
| | 1:30pm | 5:30pm | Session 15: Trajectory Design and Optimization III | Maybird |
| | 1:30pm | 5:30pm | Session 16: Spacecraft GNC II | Cirque |
| | 3:10pm | 3:30pm | Afternoon Break | Superior Lobby |
| | 6pm | 9pm | Offsite Event: The Summit (tram to mountain top) | Summit |
| ***Wednesday 22 August*** | 8am | 2pm | Registration | Front Desk Lobby |
| | 8am | 12pm | Session 17: Astrodynamics III | Superior A |
| | 8am | 12pm | Session 18: Asteroid & Non-Earth Orb. Missions II | Cirque |
| | 8am | 12pm | Session 19: Trajectory Design and Optimization IV | Maybird |
| | 8am | 12pm | Session 20: Spacecraft GNC III | Superior B |
| | 9:40am | 10:00am | Morning Break | Superior Lobby |
| | Noon | 1:30pm | AAS Technical Committee Lunch | Aerie Private Dining Room |
| | 1:30pm | 4:30pm | Session 21: Space Situational Awareness III | Cirque |

| Day | Start | End | Function | Room |
|---|---|---|---|---|
| ***Wednesday 22 August*** | 1:30pm | 4:30pm | Session 22: Attitude Dynamics & Control III | Superior B |
| | 1:30pm | 4:30pm | Session 23: Special Session – Mission Design for Spacecraft in Near Rectilinear Halo Orbits | Maybird |
| | 3:30pm | 3:50pm | Afternoon Break | Superior Lobby |
| | 4:30pm | 6:30pm | Town Hall Meeting: Astrodynamics Research Funding | Superior A |
| | 6:00pm | 7:00pm | Conference Administration Subcommittee | Cirque |
| | 6:00pm | 7:00pm | Technical Administration Subcommittee | Maybird |
| | 6:00pm | 7:00pm | Website Administration Subcommittee | Superior B |
| ***Thursday 23 August*** | 8am | 12noon | Registration | Front Desk Lobby |
| | 8am | 12:00pm | Session 24: Trajectory Design and Optimization V | Maybird |
| | 8am | 12:00pm | Session 25: Space Situational Awareness IV | Cirque |
| | 8am | 12:00pm | Session 26: Astrodynamics IV | Superior A |
| | 9:40am | 10:00am | Morning Break | Superior Lobby |

A map of the Cliff Lodge and the relevant meeting rooms appears on the next page.




## Other Summer Activities

**The Snowbird Center**
Activity Center
Wasatch Mining Company

## Meetings & Banquets

The Cliff Lodge Meeting & Banquet Rooms
Snowbird Center
The Lodge at Snowbird

## Outdoor Meeting Venues

Conference Center Terrace Tents
Creekside Terrace
Event Tent
Plaza Deck
Skier's Bridge

## Dining & Nightlife

**The Cliff Lodge**
The Aerie & Lounge
The Atrium

**The Lodge at Snowbird**
The Lodge Bistro & Lounge

**Snowbird Center**
Baked & Brewed Café
The Birdfeeder
The Forklift
General Gritts Grocery & Deli
Steak Pit
Tram Car Pizza
Tram Club

**On-Mountain**
The Summit (Top of Aerial Tram, Hidden Peak)

## Shops & Services

**The Cliff Lodge**
Cliff Sundries
The Cliff Spa & Shop
Superior Snacks
ATM
Public Safety

**Snowbird Center**
Center Sundries
Pharmacy
U.S. Post Office
Christy Sports
Smiley's Photography
Pipeline
Wings
General Gritts Wine & Liquor Store
Snowbird Sports, Bike Rental
ATM
Public Safety

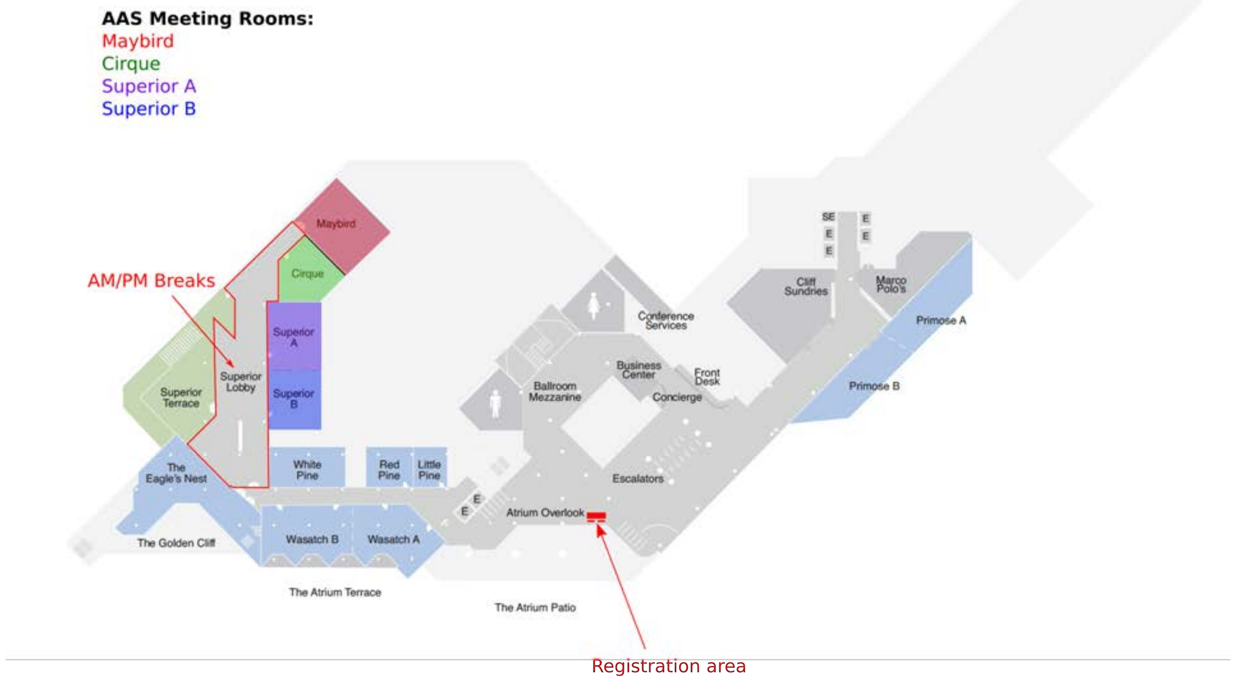
## The Cliff Spa

Fitness Room and & Classes
Roof Top Pool & Hot Tub
Spa Salon

## Construction

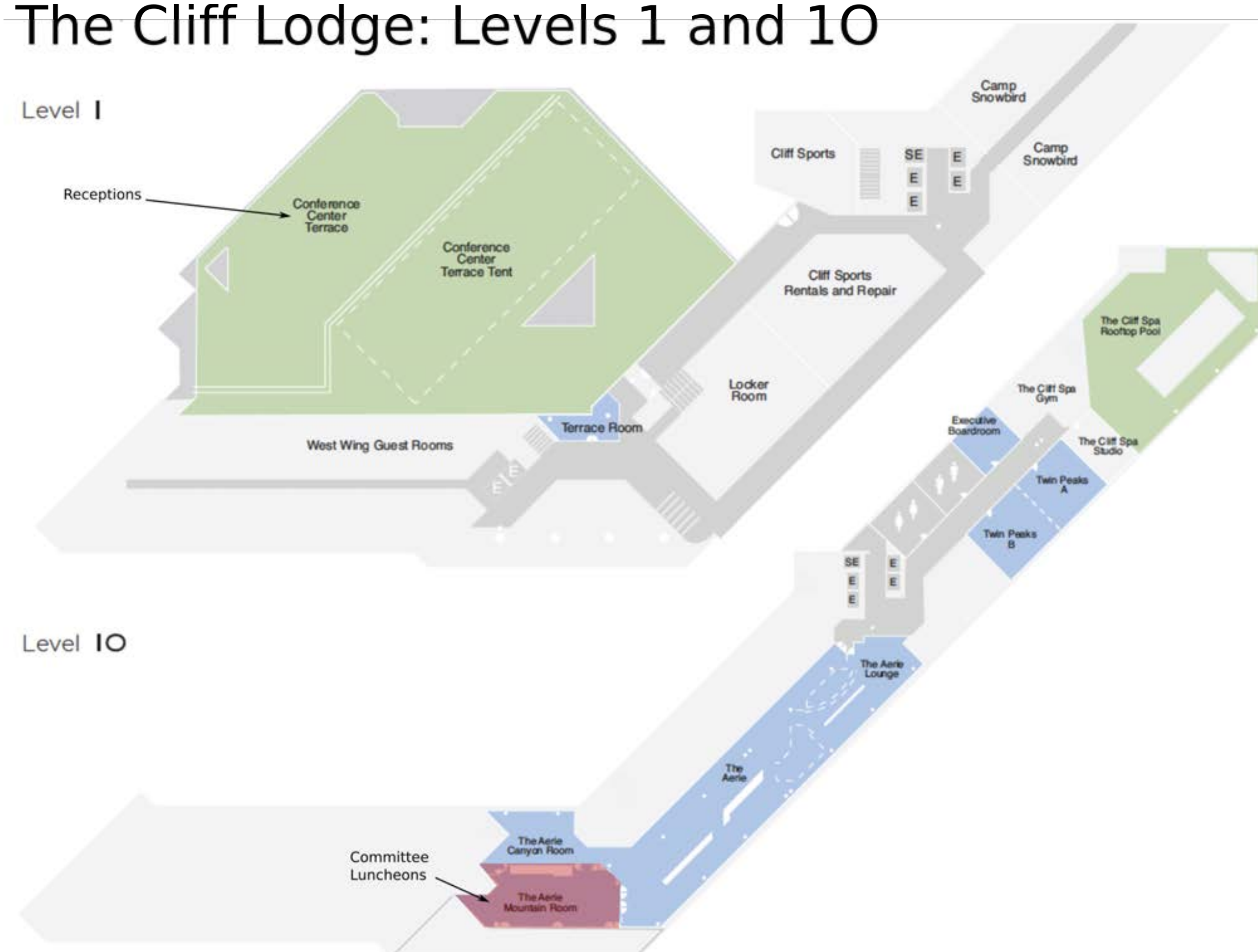
This summer, we're continuing to improve the resort we all love. Learn more at snowbird.com/improvements

# The Cliff Lodge: Lobby Level I




# The Cliff Lodge: Lower Level L

# The Cliff Lodge: Levels 1 and 10



## Special Events

### *Early Bird Reception*

Sunday, 19 August 6:00 – 9:00 pm

Location: Conference Center Terrace

### *Dirk Brouwer Award Plenary and Breakwell Travel Award Presentation:*

Monday, 20 August 5:30 – 6:30 pm (Awards Reception)

6:30 – 8:30 pm (Ceremony and Lecture)

Location: Conference Center Terrace (Awards Reception)

Ballroom 1 (Ceremony and Lecture)

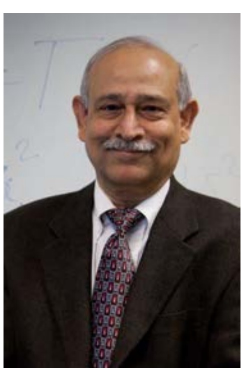
In addition to the plenary talk and travel awards, new AAS Fellows will be honored:

- Bobby Braun
- Ryan Russell
- Puneet Singla

### Fifty Years of Tethered Space Systems

The feasibility of using tethered systems in space was first demonstrated in September 1966 when Gemini XI was connected by a tether to the Agena Target Vehicle. Since then many tethered space systems have flown with various mission objectives. Tethered satellites have been proposed for scores of applications such as upper atmospheric studies, electrodynamic propulsion, creation of artificial gravity, formation flying, debris removal, etc. These proposals have led to many interesting problems in astrodynamics. Some of these problems will be discussed in the talk. Some of the recent tethered satellite missions as well as the ones to be launched in the near-term will be described.

### *Dirk Brouwer Award Honoree*



Dr. Arun K. Misra is the Thomas Workman Professor in the Department of Mechanical Engineering at McGill University in Montreal, Canada. His research interests lie in the areas of dynamics and control of tethered satellites, large space structures, formation flight and space robotics. Dr. Misra is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA) as well as of the American Astronautical Society (AAS). He has been elected to the International Academy of Astronautics and to the Canadian Academy of Engineering.

### *THE SUMMIT AT SNOWBIRD*

Tuesday, 21 August 7:00 – 9:00 pm (Plated Dinner)

Location The Summit at Snowbird

The Summit is Snowbird’s newest year-round guest facility located atop Hidden Peak at 11,000 feet. Just a few steps from the Aerial Tram, The Summit is accessible for any tram passenger whether on foot, skis, bikes or boards.

All conference registrations will receive an event ticket, which a tram ride to and from the top of the mountain. Tram service will begin at 5:45pm. Dinner will be served at 7pm.

Guest tickets are available for $70 each on the conference registration site and include the tram ride and dinner.

Conference attendees and guests are required to specify their selected dinner at the time of registration.

Options include:

- Herb roasted pork loin, pan juices, warm apple chutney, butternut squash, seasonal vegetables
- Breast of chicken saltimbocca), prosciutto, sage-caper sauce, orecchiette with broccoli and asiago
- Grilled vegetable kebabs, lemon tahini sauce, braised lentil, and pine nut pilaf

***Be sure to bring your meal ticket (provided at registration) to the event.***

## TRANSPORTATION TO/FROM THE SUMMIT

Attendess and guests will take the Aerial Tram from the Village to The Summit. Locations may be seen on the map (page 6). Tram tickets will be available at the mountain base where you board the tram. Please note that each ticket is for a single round trip, i.e., attendees will not be able to return to The Summit after completing the return trip. For those that prefer not to walk from the hotel to the tram base, there will be a shuttle available. Details on the tram and shuttle schedule follow.

| | |
|---|---|
| Trams Start Running: | 5:45pm |
| Tram Frequency: | 15 minutes |
| Ride Duration: | ~7 minutes |
| Shuttle to Tram Base: | 5:15-7pm |
| Shuttle Duration: | 5-7 minutes |
| Shuttle Frequency: | 15 minutes |
| Dinner: | 7-9:00pm |
| Last Tram from Summit: | 9:30pm |
| Shuttle to Hotel from Tram: | 8:30-10:00pm |
| Return Shuttle Frequency: | 30 minutes |

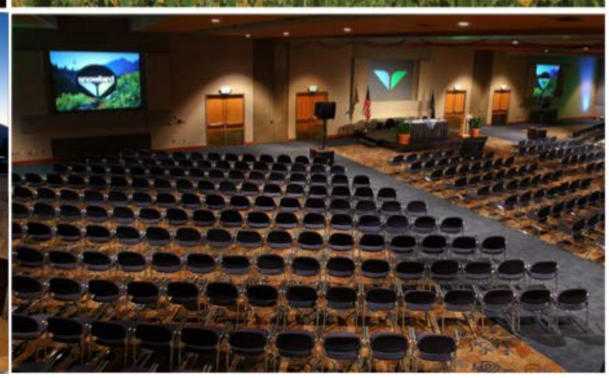
***Conference organizers highly recommend that attendees and guests begin their trip to The Summit early.*** (This also provides more opportunities to enjoy the view!) Each tram car only holds 60-70 people comfortably, and there will be 250+ people attending the offsite event. There will be five (5) tram trips available from beginning of operation until the start of dinner.

## Conference Location

### The Cliff Lodge

9320 Cliff Lodge Dr.
Snowbird, UT, 84092
https://reservations.snowbird.com/
(801) 933-2222 (voice)
1-800-232-9542 (toll-free)
1-800-453-3000 or 1801-947-8220 (Central reservation office, US callers)
00 800 4400 5511 (Reservations, international)



The Cliff Lodge at Snowbird is one of North America's most iconic ski lodges. The majesty of Little Cottonwood Canyon can be explored from the views each room provides whether facing Snowbird's ski slopes or peering down the glacially carved canyons spilling into the Salt Lake City valley below.

Within walking distance to Snowbird's pedestrian village, The Cliff Lodge offers comfortable lodging for the whole family or group. Other amenities include an exercise room, resort-wide internet service, room service, concierge and a state-licensed daycare facility. Among Snowbird's excellent selection of dining opportunities, The Aerie Restaurant and Lounge and The Atrium are open year-round and provide diverse menus for every palate.

After a day on the mountain, relax at the outdoor pool or The Cliff Spa. Open year-round, a heated swimming pool and three hot tubs are located outdoors on Level 3. Located on the 9th and 10th floors, The Cliff Spa features over 30 treatment and salon services, yoga studio, fitness center, rooftop pool and hot tub.

A room block with the Government Per Diem Rate ($117/night, $10 per additional person per night, $10 per room resort fee) will be held through **July 18, 2018**. 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 hotel (see voice number above). Please be sure to mention the group code AAS or the group name "American Astronautical Society" when making reservations in order to receive the group rate. Attendees may book rooms at the group rate either on-line or over the phone. Online bookings should use the "Group Code" **2C81OG**. When booking on-line, full payment is required at time of booking. When calling in, a one-night deposit is required at the time of booking. Either method has a 72-hour prior cancellation policy to avoid a one-night fee. Group arrival is August 18, 2018 and Group Departure is August 23, 2018.

Group Reservation Page:

https://reservations.snowbird.com/

Cancellations must be made 72 hours in advance of intended arrival.

The required resort fee includes self-parking and internet access.

## *ARRIVAL INFORMATION*

### Check-In and Checkout

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

### Parking

Self-parking is included in the resort fee when staying at the conference hotel.

## *HOTEL SERVICES AND AMENITIES*

- 24-hour Front Desk
- Concierge Service (located at the front desk)
- Room Service
- Wireless high-speed Internet access in all guest suites and public areas
- Fitness center and yoga studio
- In-room coffee
- USA Today
- Business center with first 15 minutes free
- Heated swimming pool
- Hot tub
- Cliff Spa
- Luggage Storage

## *TRANSPORTATION INFO*

The greater Salt Lake City, UT area is served by the Salt Lake City International Airport (SLC). The Snowbird Resort is located roughly 31.9 miles southeast of the Salt Lake City International Airport, approximately 41-minutes one-way. The hotel does not offer a free shuttle to/from the hotel. However, for those not traveling via rental vehicle, there are several at-cost transportation options available. The table below shows a cost comparison across some of those options, though the actual pricing should be verified directly with the appropriate vendor on the dates of travel.

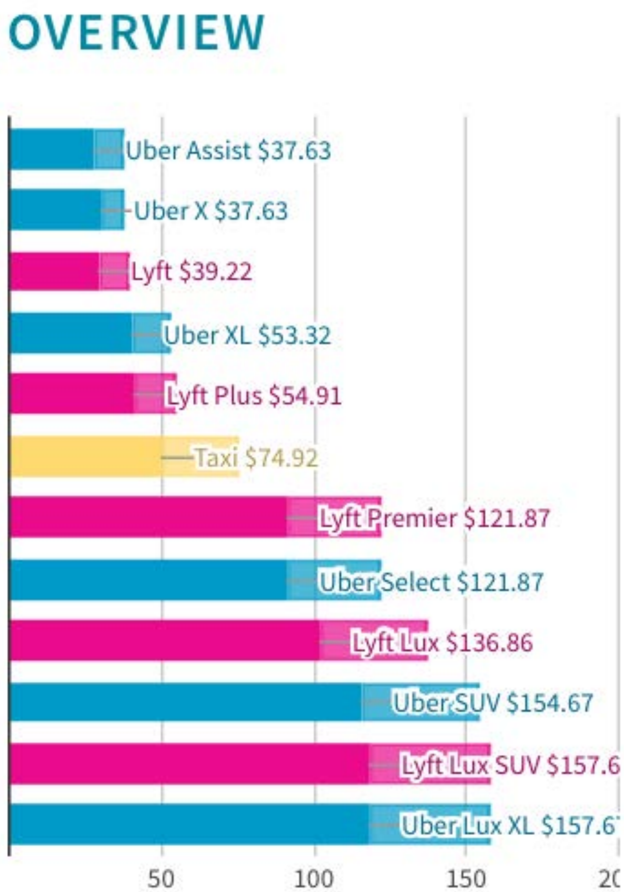



Image Source: https://ride.guru/.

A mid-range alternative, in terms is cost, is available through Canyon Transportation, as noted below. This is less expensive than a Taxi but more expensive than Uber or Lyft.

## DIRECTIONS FROM AIRPORT

FROM SLC to Snowbird, UT

Take I-80 east to I-215 south. Take Exit 6 (6200 South) and go east on 6200 South, toward the mountains. This road will lead you straight to UT-210 and up Little Cottonwood Canyon to Snowbird.

## UBER/LYFT

Uber and Lyft operate between Salt Lake City Airport and The Snowbird Resort. The costs range from the high $20’s to the mid $30’s for UberX and UberXL (see https://www.uber.com/fare-estimate/) or $43 to $60 with Lyft and Lyft Plus, (see https://www.lyft.com/fare-estimate).

## CANYON TRANSPORTATION

Phone: (801) 255-1841

Website: http://canyontransport.com/

Canyon transportation, which holds an exclusive contract with Snowbird, offers a reasonably priced shared ride service to/from the resort. Private SUV’s and vans are also available. The rates, at the time of this publication, are posted below. A shared ride arrangement costs around $82 for a round trip, or $45 one-way. Reservations are **highly recommended**, but you can also visit their desk at the airport and they will do their best to get you to the resort in a timely fashion.

| | **One Way** | **Round Trip** |
|---|---|---|
| Shared Ride | | |
| Adult | $45 | $82 |
| Children – Under 12 | $28 | $55 |
| Private SUV (1-4 passengers) | $180 | $360 |
| Private Van (1-5 passengers) | $225 | $450 |
| Private Van (6 passengers) | $230 | $460 |
| Private Van (7-8 passengers) | $255 | $510 |
| Private Mini Coach (1-14 passengers) | $320 | $640 |

Pricing Source: http://canyontransport.com/rates-reservations/

## TAXI

Taxi service between SLC and Snowbird is available. The estimated one-way fare (at the time of publication) is $75.

## *AREA ATTRACTIONS*

The Cliff Lodge is located at the mountain based in Snowbird, UT. In the summer, the resort offers a variety of activities for families (aerial tram, mountain coaster, ropes course, etc.) and more adventurous adults (vertical drop, mountain biking). Details on these activities and more, including how to make reservations where required, may be found at http://www.snowbird.com.

## SNOWBIRD OKTOBERFEST

Snowbird is holding its annual Oktoberfest Aug. 18-Oct. 21. This event is held Sat.-Sun., 12 noon-6:30pm every weekend during that time, and admission is free. Early arrivals may sample a variety of beers from American pale ales to stouts made with a wide variety of hops and brew methods. This annual festival was voted one of America’s 10 Best Oktoberfests by Men’s Journal Magazine. More details on the event may be found at https://www.snowbird.com/oktoberfest/.

## SNOWBIRD CENTER

The Snowbird Center, which is within walking distance of The Cliff Lodge, offers a variety of dining, nightlife, and shopping venues. A map of the center may be found at:

https://www.snowbird.com/uploaded/meetings-pdfs/snowbird_villagemap.pdf

## ADDITIONAL INFORMATION

### *SPEAKER ORIENTATION*

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 **Friday August 17th, 2018, 23:59:59 Eastern Time**. Authors are required to maintain close correspondence with your Session chair regarding the presentations of your manuscript. Please be in the 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 **August 10, 2018, 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.

## *PRE-PRINTED 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. Robert D. Braun, Georgia Institute of Technology
Manuscripts can be submitted via: https://mc.manuscriptcentral.com/aiaa

## *SATISFACTION SURVEY*

Registrants are highly encouraged to record their level of satisfaction and conference preferences in an anonymous survey taken throughout the time of the conference. Please return the survey form given to you when you check in at the registration table to the registration table before departing from the conference.

## *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 Technical Session Schedule

Last Update: 13 August 2018

The Most Up-toDate Full Schedule at : https://www.xcdsystem.com/aas/program/tech_program.cfm

The web interface at https://www.xcdsystem.com/aas/program/OjvenM6/index.cfm

# Monday August 20, 2018

### Aug 20, 2018 Superior A – Astrodynamics – I

**Monday Session 1 Astrodynamics - 1**

Chair: Jeff Parker, Advanced Space
Co-Chair: Matthew Wilkins, Applied Defense Solutions

**8:00** **AAS 18-214** **A monotonic starter for solving the hyperbolic Kepler equation by Newton's method**

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

This communication deals with the iterative solution of the sine hyperbolic Kepler's equation (SHK): F_g(S) = S - g arcsinh(S) ? L = 0. Since this function is monotonic increasing and convex, any starter value S_0 such that F_g( S_0 ) > 0, leads to a a Newton's sequence S_j monotic decreasing to the exact solution of SKE equation and therefore has some advantages over non monotonic starters. Because of this, we are able to construct a monotonic starter such that minimizes the computational cost and that guarantees super-convergence by applying an optimal version of Newton-Kantorovich theorem.

**8:20** **AAS 18-252** **Phobos's Rotational Dynamics**

*James Miller, Consultant; Gerald Hintz, University of Southern California*

As Phobos orbits Mars, it is subjected to a torque that gives rise to an oscillation about the line connecting the center of Mars with the center of Phobos. This oscillation is referred to as libration and has an amplitude of about one degree. The source of the torque is the variation or gradient of the gravity of Mars across Phobos. An equation is derived that includes forced and transient terms.

**8:40** **AAS 18-267** **ANALYSIS OF THE EFFECT OF OBLATENESS IN THE CIRCULAR RESTRICTED THREE BODY PROBLEM NEAR THE SECONDARY BODY**

*Luke Bury, University of Colorado Boulder*

The Circular-Restricted Three-Body Problem (CR3BP) is widely used for calculating baseline trajectories. However, solutions obtained with the classic CR3BP are not dynamically robust. The CR3BP makes large assumptions such as the circular motion of bodies and point-mass gravitation. The purpose of this paper will be to refine the CR3BP through the addition of the primary body's oblateness (J2) and provide analysis on the effect of this addition near the secondary body in real systems. Metrics considered include zero-velocity curves, collinear equilibria point location, periodic orbit behavior, and minimum necessary delta-V for landing on a secondary.

**9:20** **AAS 18-370** **An ecliptic perspective for analytical satellite theories**

*Ioannis Gkolias, Politecnico di Milano; Martin Lara; Camilla Colombo, Politecnico di Milano*

Traditionally, the forces in analytical theories for Earth satellite orbits are expressed in a coordinate frame which involves the equatorial plane. However, for distant satellites, the Moon and Sun attractions are equally important, and those forces are expressed more conveniently in a frame associated to the ecliptic plane. In this work, we develop an analytical satellite theory in which all the forces are expressed with respect to the ecliptic plane. The main advantage of the method is that, after the averaging process, all time-dependent terms disappear from the formulation yielding a model suitable for preliminary design of frozen orbits.

**9:40** **Break**

**10:00** **AAS 18-374** **Linear Covariance-Based Navigation and Maneuver Requirement Determination Using Second-Order Cone Programming for Elliptical Rendezvous Operation**

*Kai Jin, Utah State University; David Geller, Utah State University*

A novel navigation and maneuver requirement determination approach for elliptical rendezvous operation is developed in this paper. This approach can quickly determines the optimal navigation and maneuver performance meeting trajectory dispersion requirements. First,the trajectory dispersion with navigation and maneuver execution error is modeled using linear covariance analysis theory. Using the trajectory dispersion as the optimization constraint, the navigation and maneuver requirement determination problem is formulated as a second-order cone programming problem and solved. In order to apply this approach on a perturbed elliptical orbit rendezvous mission, a new state transition matrix is calculated.Simulations show that the approach works well.

**10:20** **AAS 18-389** **On the Evolution of Orbits about Active Comets**

*Mark Moretto, University of Colorado Boulder; Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)*

Spacecraft and large particles orbiting an active comet are perturbed by gas drag from the coma. These gasses expand radially at about 0.5 km/s, much faster than orbital velocities that are on the order of meters per second. The coma is not spherically symmetric.

Accelerations from gas drag can be on the same order of gravity and are currently poorly understood. We present semi-analytical solutions for the evolution of the Keplerian orbital elements of a spacecraft orbiting a comet. Implications for trajectory design, operations, and natural particle dynamics about the comet are shown.

**10:40** **AAS 18-396** **SEARCHING FOR ORBITS AROUND EQUILIBRIUM POINTS IN A BINARY ASTEROID SYSTEM MODELED AS A MASS DIPOLE**

*Leonardo Torres, INPE; Priscilla Andressa Sousa-Silva, São Paulo State University - UNESP; Diogo Sanchez, National Institute for Space Research - INPE; Antonio Fernando Bertachini Prado, INPE*

The objective of the present work is to search for orbits around the equilibrium points L1 and L2 of the restricted synchronous three-body problem. From the equations of motion of a binary asteroid system, where one of the asteroids is modeled as a rotating mass dipole, the initial conditions for the Lyapunov orbits were determined. A family of orbits was constructed around the equilibrium points L1 and L2. It is intended next to find homoclinic and heteroclinic orbits around this region.

**11:00** **AAS 18-404** **Bounded Motions Near Resonant Orbits in the Earth-Moon and Sun-Earth Systems**

*Natasha Bosanac, University of Colorado, Boulder*

Periodic and quasi-periodic trajectories in resonant orbit families contribute to an underlying dynamical structure that governs motion within a multi-body system. Characterization of both types of bounded motion in the circular restricted three-body problem is useful when compiling an expanded design space for mission orbit selection and trajectory construction. To achieve a complete representation of the quasi-periodic orbits within resonant orbit families, a continuation strategy that can avoid tori with frequencies near integer ratios is presented. This strategy is leveraged to compute and characterize quasi-periodic orbits in various interior and exterior resonant orbit families in the Sun-Earth and Earth-Moon systems.

**11:20** **AAS 18-426** **Mean Values in Elliptic Motion: Averaging the Legendre Polynomials**

*Aaron J. Rosengren, University of Arizona; Jeremy Correa, University of Arizona; Daniel Scheeres, University of Colorado at Boulder*

Averaging, being one of the oldest and most developed topics of investigation in celestial mechanics, provides a particularly effective method for the approximate evaluation of the dynamics of a system. We will present a systematic approach for computing the mean values of any particular function encountered in elliptic motion. We will show that all orbital averages occurring in perturbed Keplerian motion (assuming non-commensurate orbital frequencies) reduce to averages of certain powers of the orbit radius; thereby revealing the fundamental significance and profundity of Hansen's coefficients. This method will be applied to averaging the Legendre expansion of various gravitational potentials.

**11:40** **AAS 18-456** **On the Solution to Every Lambert Problem**
*Ryan Russell, The University of Texas at Austin*

The parameter and solution space for the zero- and multi-rev Lambert's problem is surveyed, including a close inspection of typical stress cases. The problem domain is shown to be rectangular under the recent vercosine formulation, making the elusive initial guess for Lambert's problem amenable for interpolation. Smooth, two-dimensional interpolated functions are generated over the full domain for up to 100 revolutions, focusing on methods that reduce evaluation runtime. Resulting functions yield initial guesses to solve Lambert's equation, or may be used directly as low-resolution solutions. The functions are archived and benchmarked for accuracy, speed, and memory footprint.

**Aug 20, 2018 Superior B – Proximity Missions & Formation Flying – I**

## Monday Session 2 Proximity Missions, & Formation Flying-I

Chair: David B. Spencer, Pennsylvania State University
Co-Chair: Waqar Zaidi, Applied Defense Solutions

**8:00** **AAS 18-444** **Demonstration of a propellantless spacecraft hopping maneuver on a planar air bearing test bed**
*Andrew Bradstreet, Naval Postgraduate School; Josep Virgili-Llop, Naval Postgraduate School; Marcello Romano, Naval Postgraduate School*

During on-orbit servicing or exploration of small planetary bodies, robotic spacecraft may need to move between locations on the surface of their target object. Hopping is a low gravity mobility approach where a vehicle with robotic manipulators "jumps" between two locations. The experimental demonstration of a propellantless hopping maneuver on a planar air bearing test bed with a vehicle equipped with two robotic manipulators is presented here. This is the first time, to the best knowledge of the authors, that this kind of hopping maneuver has been tested on a dynamic hardware-in-the-loop test bed.

**8:20** **AAS 18-212** **Collocation of Geostationary Satellites in Wheel Cluster Formation**
*Chia-Chun Chao, The Aerospace Corporation*

The concept of a wheel cluster formation in a single orbit plane has been demonstrated to be cost effective in deployment and formation-keeping. This paper further demonstrates through numerical simulations how the concept can be applied to the collocation of several geostationary satellites. Both east/west and north/south stationkeeping with a tight control box of +/-0.1 deg are simulated with sun-pointing constraint. Two control methods are explored. One method assumes ground control of the sub-satellites, while the other method employs the auto-feed-back controller with onboard GPS measurements. The number of collocated satellites can be 10 or more depending on navigation capability.

**8:40** **AAS 18-218** **Linearized Relative Orbital Motion Model About an Oblate Body Without Averaging**

*Ethan Burnett, University of Arizona; Eric Butcher, University of Arizona; Andrew J. Sinclair, Air Force Research Laboratory; Alan Lovell, Air Force Research Laboratory*

A new linearized differential equation model and solution for spacecraft relative motion about an oblate body is obtained without averaging the perturbing acceleration, and presented for the case of near-zero chief orbit eccentricity. The model is stand-alone and does not require integration of the chief orbit, while the time-explicit solution depends only on initial chief orbital elements, time since epoch and node crossing, and the deputy's initial conditions in the chief Hill frame. The resulting model outperforms previous models obtained via averaging, and has a similar error to the GA-STM for zero initial chief orbit eccentricity.

**9:00** **AAS 18-223** **Trajectory Optimization for Rendezvous with Bearing-only Tracking**

*Xiaoyu Chu, Beijing Institute of Technology; Kyle T. Alfriend, Texas A&M University; Jingrui Zhang; Yao Zhang*

This study focuses on an issue of trajectory optimization in spacecraft rendezvous when using bearing-only target tracking. The observability of the spacecraft in the relative motion is analyzed and verified. The rendezvous trajectory is generated by optimizing the relevant parameters in the filtering process. Two optimization algorithms are presented. The first is to minimize the trace of the filter covariance matrix, while the second is to maximize the determinant of the Fisher information matrix (FIM). By balancing these performance indices of observability with fuel consumption, the trajectory is optimized with eclectically optimum performance.

**9:20** **AAS 18-228** **Methods for Passive Optical Detection and Relative Navigation for Rendezvous with a Non-Cooperative Object at Mars**

*Alan Didion, NASA Jet Propulsion Laboratory; Austin Nicholas, Jet Propulsion Laboratory/Caltech; Joseph Riedel, NASA Jet Propulsion Laboratory; Robert Haw, NASA / Caltech JPL*

Long-range passive optical detection of an orbiting inert sphere by a robotic Mars orbiter is investigated and trades are described in terms of detectability via visible light in the presence of orbit uncertainty, gravitational perturbations, and camera electronics noise. A new approximate equation for signal-to-noise ratio (SNR) is developed to include most relevant camera imperfections, diffraction, and stray light from the Mars limb as relevant to this scenario. Using this method, a notional camera suite is designed to meet detection, navigation, and redundancy requirements for an example mission scenario. Navigation analysis results suggest the rendezvous is feasible with current technology.

**9:40** **Break**

**10:00** **AAS 18-231** **Algorithms for Small Satellite Formation Initialization**

*Robert LaRue, U.S. Air Force; Kirk W. Johnson, US Air Force*

This study examines the initialization of SmallSat (small satellite) formations. Guidance and control algorithms are developed to generate fuel-optimal formation initialization trajectories. The maneuver solutions generated by the algorithms are assessed by a numerical propagation using the nonlinear equations of motion with $J_2$ and drag perturbations. Initial conditions are chosen to simulate dispersal from a carrier vehicle. Methods are presented for negating spacecraft relative velocity in the context of formation initialization. The developed algorithms are used to examine a variety of scenarios and draw conclusions about the effect of various design parameters in the context of formation initialization.

**10:20** **AAS 18-278** **A MINIMAL PARAMETERIZATION ON SIX D.O.F. RELATIVE ORBITAL MOTION PROBLEM USING DUAL LIE ALGEBRA**

*Daniel Condurache, Technical University of Iasi*

This main goal of this research is the development of a new approach of minimal parameterization to the full-body relative orbital motion problem. Using the isomorphism between the Lie group of the rigid displacements and Lie group of the orthogonal dual tensors, a solution of the problem is obtained. A representation theorem of the 6-DOF relative orbital motion problem is given. Using the Euler dual vector, the higher-order Rodrigues dual vector or Davenport-Euler dual angles the minimal dimensional representations of this problem is obtained. The novelty of the method over existing solutions is discussed and the main advantages are revealed.

**10:40** **AAS 18-312** **State-Dependent Riccati Equation Control for Spacecraft Formation Flying in the Circular Restricted Three-Body Problem**

*Michael Tannous, University of Pisa - Department of Information Engineering; Giovanni Franzini, University of Pisa - Department of Information Engineering; Mario Innocenti, University of Pisa - Department of Information Engineering*

The use of the state-dependent Riccati equation (SDRE) technique for formation flying control in the circular restricted three-body problem is investigated in this paper. First, the relative dynamics of a leader-follower formation is described by computing the difference between the equations of motion associated to the two spacecraft. Then, a pseudo-linear form of the relative motion equations is identified in order to implement the SDRE control technique. The effectiveness of the controller is proved by the high accuracy and the limited control usage achieved during the numerical simulations, set up considering the New Worlds Observer mission scenario.

**11:00** **AAS 18-326** **A Semi-analytical Approach to Characterize the Relative Motion in the Vicinity of Phobos**

*Davide Conte, Pennsylvania State University; David B. Spencer, Pennsylvania State University*

This paper discusses a semi-analytical approach to approximate the relative motion of spacecraft around Distant Retrograde Orbits (DROs) in the vicinity of Phobos. Numerical analysis reveals that Mars-Phobos DROs can be represented in a moderately accurate way using second-order Fourier series representations. Assuming that the relative distance between spacecraft is small, the equations of motions can be simplified and written directly using time-dependent coefficients which can then be semi-analytically solved to obtain a representation of the relative motion. These equations exhibit a secular behavior, accurately described by the Hill-Clohessy-Wiltshire equations, and a short-term cyclic behavior due to the Phobos' gravity.

**11:20 AAS 18-339 ARC-LENGTH SOLVER METHODOLOGY FOR RELATIVE ORBIT DETERMINATION MEASUREMENT EQUATIONS**

*Brett Newman, Old Dominion Univ.; Alan Lovell, Air Force Research Laboratory; Geoffrey Rose, NASA Langley Research Center; Duc Nguyen, Old Dominion University*

Numerical solution of an algebraic formulation of the Keplerian circular relative orbit determination problem is investigated using iterative nonlinear arc-length solver methodology. A series of angular measurements are coupled to an approximate analytic relative motion solution. The resulting set of nonlinear measurement equations are solved for six unknown deputy initial conditions. The arc-length method computes a continuous family of solutions using an unknown continuation parameter. From this family, specific solutions corresponding to a zero parameter value are extracted. The method avoids concerns related to start value selection, convergence to trivial-undesired solutions, divergence to infinite valued solutions, and numerical ill-conditioning.

**11:40 AAS 18-420 Real-Time Angular Velocity Estimation of Non-Cooperative Space Objects Using Camera Measurements**

*Marcelino Mendes de Almeida, The University of Texas at Austin; Maruthi R. Akella, University of Texas at Austin; Daniele Mortari, Texas A&M University; Renato Zanetti, University of Texas at Austin*

This paper presents a solution to the problem of estimating the relative angular velocity (RAV) between a camera (onboard a chaser spacecraft) and an object in space (the target spacecraft or celestial object) using camera measurements only. Our approach assumes no prior knowledge of the initial characteristics of the target, making it seamlessly applicable to different applications. Our algorithm pipeline uses SLAM to estimate the relative pose, which is used as inputs to a Discrete Adaptive Angular Velocity Estimator (estimates the Angular Velocity Direction) and a modified MEKF (estimates the Angular Velocity Magnitude).

**Aug 20, 2018 Maybird – Trajectory Design & Optimization – I**

## Monday Session 3 Trajectory Design & Optimization-I

Chair: Roby Wilson, Jet Propulsion Laboratory

**8:00 AAS 18-251 2018 Mars InSight Mission Design and Navigation Overview**

*Fernando Abilleira, NASA Jet Propulsion Laboratory/Caltech*

Originally scheduled for a launch in the 2016 Earth to Mars opportunity, NASA's Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) mission will launch the next lander to Mars in May-June 2018 arriving to the Red Planet in November 2018. Derived from the Phoenix mission which successfully landed on Mars in May 2008, the InSight Entry, Descent, and Landing system will place a lander in the Elysium Planitia region. This paper specifies the mission and navigation requirements set by the Project and how the final mission and navigation design satisfies those requirements.

**8:20 AAS 18-246 Enhanced Station-Keeping Maneuver Control Technique for Delta-V Cost Reduction in Korea Pathfinder Lunar Orbiter**

*Jae-ik Park, Korea Aerospace Research Institute; Diane Davis, a.i. solutions, Inc.; Su-JIN Choi, Korea Aerospace Research Institute; Ryan Whitley, NASA; John P. Carrico, Space Exploration Engineering, Inc.; Dong-Young Rew, Korea Aerospace Research Institute; Seok-Weon Choi, Korea Aerospace Research Institute*

This paper proposes an enhanced control technique for station-keeping maneuvers to reduce delta-V costs for the Korea Pathfinder Lunar Orbiter (KPLO). The reduction is demonstrated by comparing the proposed technique against previous algorithms implemented for maneuver operations of the Lunar Reconnaissance Orbiter (LRO) in USA and KAGUYA in Japan. A scheduled circularization control technique combines the advantageous points of the two methods to achieve a significant reduction in station-keeping delta-V costs. Through Monte Carlo analysis, the efficacy and robustness of the proposed method are verified, and the technique is shown to meet the operational requirements of KPLO.

**8:40 AAS 18-250 MMS Extended Mission Design: Evaluation of a Lunar Gravity Assist Option**

*Trevor Williams, NASA/Goddard Space Flight Center; Dominic Godine, ai Solutions, Inc.; Eric Palmer, ai Solutions, Inc.; Ishaan Patel, ai Solutions, Inc.; Neil Ottenstein, a.i. solutions, Inc.; Luke Winternitz, NASA Goddard Space Flight Center; Steven Petrinec, Lockheed Martin Advanced Technology Center*

This paper describes maneuvers that were recently considered for a later extended mission phase for the Magnetospheric Multiscale (MMS) mission. These are apogee-raises to set up a lunar gravity assist, which in turn raises perigee for enhanced magnetopause science collection. Since a lunar encounter is only achievable when the MMS apogee vector lies approximately in the lunar orbit plane, the possible dates are mid-2021 or early 2027. This study was made feasible by the fact that MMS is consuming fuel for formation maintenance far slower than expected pre-flight, and completed the prime mission with a significant amount of fuel remaining.

**9:20** **AAS 18-259** **Evaluation of Optimal Control Algorithms Used in Spacecraft Maneuver Planning**

*Chris Lawler, The US Naval Research Laboratory*

Because of the nonlinearity present in the equations of motion for practical satellite orbit dynamics, optimal control is essential in determining an appropriate maneuver sequence to correctly change a satellite's state above the Earth. A maneuver planning and analysis toolkit is currently under development at the US Naval Research Laboratory that will streamline calculation of maneuver sequences that satisfy specific mission goals. The optimal control algorithm used in this toolkit, the E04UFF algorithm provided by the Numerical Algorithms Group will be compared with AGI Astrogator's differential corrector to verify this toolkit's effectiveness in solving spacecraft maneuver planning problems.

**9:40** **Break**

**10:00** **AAS 18-262** **TRAJECTORY ANALYSIS OF A SPACECRAFT MAKING A THREE-DIMENSIONAL POWERED SWING-BY MANEUVER**

*Alessandra Ferreira, Universidade Estadual Paulista - UNESP; Rodolpho Moraes, UNIFESP; Antonio Fernando Bertachini Prado, INPE; Othon Winter, Universidade Estadual Paulista -UNESP*

This paper proposes to study orbital maneuvers performed by the passage of a spacecraft near of a celestial body with impulsive propulsion, considering the movement of the space vehicle in the three-dimensional space, thus allowing the orbital plane change. This type of maneuver can send the probe to a point far from the orbit or to cause the capture or escape of the spacecraft by the celestial body. The effects of the orbit change on the energy and angular momentum of the spacecraft will be presented, as well as the types of orbits and inclination resulting from this change.

**10:20** **AAS 18-271** **Arcus Mission Design: Stable Lunar-Resonant High Earth Orbit for X-Ray Astronomy**

*Laura Plice, Metis Technology Solutions; Andres Dono Perez; Lisa Policastri, Space Exploration Engineering (SEE); John P. Carrico, Space Exploration Engineering, Inc.; Michel Loucks, Space Exploration Engineering (SEE)*

The Arcus mission, proposed for NASA's 2016 Astrophysics Medium Explorer (MIDEX) announcement of opportunity, will use X-ray spectroscopy to detect previously unaccounted quantities of normal matter in the Universe. The Arcus mission design uses 4:1 lunar resonance to provide a stable orbit for visibility of widely-dispersed targets, in a low background radiation environment, above the Van Allen belts for the minimum two-year science mission. Additional advantages of 4:1 resonance are long term stability without maintenance maneuvers, eclipses under 4.5 hrs, perigee radius approx. 12 Re for data download, and streamlined operational cadence with approx. 1 week orbit period.

**10:40** **AAS 18-276** **Optimal trajectories for a dual-spacecraft outer planet mission**

*Hongwei Yang, Nanjing University of Aeronautics and Astronautics; Wei You, Shanghai Institute of Satellite Engineering; Shuang Li, Nanjing University of Aeronautics and Astronautics; Xiuqiang Jiang, Nanjing University of Aeronautics and Astronautics*

A hypothetical future dual-spacecraft mission for visiting Jupiter and Uranus is considered in this paper. The constrained impulsive trajectory optimization method using the particle swarm optimization algorithm is proposed for the design trajectory of the mission. In trajectory optimization, Venus-Earth-Earth-Jupiter gravity assists are employed. For low-thrust case, an indirect method is employed for trajectory optimization based on the impulsive-thrust trajectories. A technique for solving hybrid-thrust trajectories is also presented. Analyses on the mission fuel consumption are conducted based on optimized trajectories. The obtained results are expected to provide reference for future missions.

**11:00** **AAS 18-277** **Mission Analysis for an ESA contribution to the Mars Sample Return campaign**

*Eric Joffre, Airbus Defence and Space Ltd; Uwe Derz, Airbus Defence and Space Ltd; Marie-Claire Perkinson, Airbus Defence and Space Ltd; Jakob Huesing, ESA; Friederike Beyer, ESA; Jose Manuel Sanchez Perez, ESA*

Bi-lateral discussions between NASA and the European Space Agency identified the orbiter element as a promising European-led contribution to a future international Mars Sample Return campaign. Airbus recently completed the Mars Sample Return Architecture Assessment Study on behalf of ESA, with the objective to identify and quantify candidate mission architectures. The paper will describe the mission analysis that was conducted to support preliminary system design, launch mass estimation and mission timeline for the architectures investigated. It includes the extensive optimisation of interplanetary transfers (with Chemical and Electric Propulsion), Mars operations including aerobraking and rendezvous, up to Earth re-entry conditions.

**11:20** **AAS 18-269** **A Convex Optimization Approach to Mars Entry Trajectory Updating**

*Connor Noyes, University of California, Irvine; Kenneth Mease, University of California, Irvine*

A trajectory updating scheme is proposed for Mars entry guidance. The trajectory generation problem is posed as an optimal control problem. The problem is convexified and solved using convex optimization. Unlike previous convex approaches to entry guidance, there is no iteration required and only a single optimization problem is solved. The trajectory may be updated at fixed intervals or when the predicted final state does not match the target state. The update scheme is applicable in reference trajectory tracking guidance algorithms as well as in the role of predictor-corrector guidance. The effectiveness of the method is demonstrated via numerical simulation.

**11:40** **AAS 18-349** **TRACKING CONTROL OF SPACECRAFT ATTITUDE AND POSITION ON TIME DEPENDENT TRAJECTORIES USING DUAL QUATERNIONS**

*Ali Tevfik Büyükkoçak, Middle East Technical University; Ozan Tekinalp, METU Aerospace Engineering Dept.*

Spacecraft attitude and position control algorithm which uses dual quaternions for parametrization is proposed. Error dual quaternion and its derivative are obtained from the desired attitude and position which are the trajectories of time dependent functions. This position and orientation (pose) formulation is used with a Lyapunov based feedback control law that includes derivative of desired attitude and position. Simulation results show that desired attitude and position trajectories are tracked successfully by the new algorithm.

**Aug 20, 2018 Cirque – Space Situational Awareness – I**

**Monday Session 4 Space Situational Awareness-I**

Chair: Christopher Roscoe, Applied Defense Solutions
Co-Chair: Kyle DeMars, Missouri University of Science and Technology

**8:00** **AAS 18-213** **Accurate and Efficient Collision Probability for Nonlinear Covariance**

*William Todd Cerven, Aerospace Corporation; Felix Hoots, Aerospace Corporation*

The location of a satellite in space is typically described by an element set or state vector at some epoch and the location uncertainty is described by a covariance. The probability density function is usually assumed to be Gaussian. Nonlinearities can introduce significant errors in the propagation of the covariance and have been a topic of several recent papers. We have developed a method to remove most of the nonlinearities and provide accurate propagation of the uncertainty estimate for 30 days or more. This paper demonstrates how the resulting covariance can be used to compute an accurate probability of collision.

**8:20** **AAS 18-355** **Dynamic Sensor Steering for Target Search for Space Situational Awareness**

*Mihir Patel, University of Illinois at Urbana-Champaign; Andrew J. Sinclair, Air Force Research Laboratory; Hoong Yeong, University of Illinois; Ryne Beeson, University of Illinois at Urbana-Champaign; Koki Ho, University of Illinois, Urbana-Champaign*

This paper will develop a method for efficient sensor steering planning to search and detect an orbiting space objects in an highly uncertain or unknown orbit using an imperfect sensor. This problem is important for orbital sensors to perform follow-up observations of an uncorrelated track (UCT). This paper will address this important literature gap by creating a particle-based estimation methodology with clustering strategies to make the search process more efficient. The resulting methods will be integrated into existing information theoretic search strategies and the performance will be evaluated by simulations.

**8:40** **AAS 18-357** **Analysis And Design Of Collision Avoidance Maneuvers For Passive De-Orbiting Missions**

*Juan Luis Gonzalo, Politecnico di Milano; Camilla Colombo, Politecnico di Milano; Pierluigi Di Lizia, Politecnico di Milano*

Collision avoidance maneuvers (CAMs) for passive de-orbiting missions using sails are studied, maneuvering either the sail or the incoming object. Analytical and semi-analytical expressions for the CAM are obtained leveraging the proximal motion equations, maximizing either the total or b-plane contained deviation. When the sail performs the CAM, different attitude-related strategies are investigated. The required amount of propellant or sail maneuverability as function of the lead time is traded-off. Finally, representative test cases are proposed based on data from ESA's MASTER tool, and the evolution of the covariance matrix with the lead time is investigated.

**9:00** **AAS 18-377** **Physically-Constrained Inverse Optimal Control for Satellite Maneuver Detection**

*Richard Linares, University of Minnesota; JOSEPH RAQUEPAS, Air Force Research Laboratory*

This paper develops an approach to determine the behavior of Space Objects (SOs) using Inverse Reinforcement Learning (IRL) and Inverse Optimal Control (IOC) theory. The proposed approach determines the reward function that each SO is using for control utilizing both IRL and IOC theory, thereby determining the behavior of the SOs. The approach discussed in this work can be used to analyze maneuvering SOs from observational data. The contribution of this work is to formulate the IRL problem using IOC theory. The IRL problem is solved using the Pontryagin's minimum principle.

**9:20** **AAS 18-381** **Early trajectory estimate of proximate objects with an optical fence**

*Liam Healy, Naval Research Laboratory; Scott Kindl, Naval Research Laboratory; Christopher Binz, Naval Research Laboratory; Christoph Englert, NRL; Andrew Nicholas, Naval Research Laboratory*

A on-board optical ``fence'' that provides angles-only relative orbital knowledge of objects in its vicinity can be used to make early estimates of the relative orbit. A relative orbit can be estimated from three or more observations except for the scale. Observable relative motion is described by just three parameters instead of the full six; estimating a smaller number of parameters gives better estimates. The most interesting is the relative drift rate, as this determines how long the objects stay close. The estimated uncertainties for each parameter and their variation with different orientation of the fence is studied.

**9:40** **Break**

**10:00** **AAS 18-441** **A Direct Light Curve Inversion Scheme for Artificial Objects**

*Siwei Fan, Purdue University; Carolin Frueh, Purdue University*

While the orbit of a space object is referred to as its first degree of characterization usually done through orbit determination, the second degree of characterization involves revealing information like the object shape and its attitude. For objects in LEO and GEO with significant reflection property, it is possible to observe their reflected brightness with telescopes in the visible spectrum. The paper presents a direct inversion scheme that takes the brightness history as input. It is explicitly investigated how measurement errors directly affect the result of the inversion process.

**10:20** **AAS 18-443** **INFORMATION METRICS FOR OBSERVATION-TO-TRACK ASSOCIATION**

*Michael Mercurio, Applied Defense Solutions; Eamonn Moyer, Applied Defense Solutions; Matthew Wilkins, Applied Defense Solutions; Paul Schumacher, Air Force Research Laboratory*

The classical data association problem, also known as observation-to-track association, is of particular importance in astrodynamics. Filtering frameworks allow for the fusion of dynamic state predictions with imperfect observations to obtain updated ephemeris estimates. Due to the agnostic measurement update step, knowledge of true observation-to-track associations must be known a-priori. This research proposes the use of information-based metrics as a discriminator for ambiguous observation-to-track associations. Metrics such as Mutual Information and various Information Divergence measures will be investigated for applicability to the classical observation-to-track association problem.

**10:40** **AAS 18-459** **SPACECRAFT MANEUVER DETECTION USING OPTIMAL CONTROL THEORY AND RELATIVE EQUATIONS OF MOTION**

*Atri Dutta, Wichita State University; JOSEPH RAQUEPAS, Air Force Research Laboratory*

In this paper, we consider an optimal control formulation for the spacecraft maneuver detection problem using the Hill-Clohessy-Wiltshire equations of relative motion and Lp norm of the control variables as the objective function. Necessary conditions of optimality are investigated to analytically compare the performance of L1 and L2 norms. Both deterministic and stochastic formulations for the optimal control problem are considered. Using numerical simulations, we compare the performance of the different optimal control formulations, as well as the impact of considering nonlinear equations of relative motion.

**11:00** **AAS 18-461** **Parallel Markov Chain Monte Carlo for Sensor Scheduling**

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

In this paper, we present a  parallel Markov Chain Monte Carlo based solution to the sensor scheduling problem. In the context of space situational awareness, the objective of sensor scheduling is to maximize the information gain from observing a large number of space based targets using a limited number of sensors. The parallel MCMC approach is a sampling based optimzation approach that can explore the action space more efficiently than a single markov chain. The parallel MCMC method is combined with a receding horizon approach to compute the optimal action sequence over a moving window.

**11:20** **AAS 18-468** **Angles-Only Navigation for Autonomous On-Orbit Space Situational Awareness Applications**

*Joshua Sullivan, Stanford University; Alan Lovell, Air Force Research Laboratory; Simone Damico, Stanford University*

This paper develops an algorithmic framework for the initialization and sequential implementation of an autonomous angles-only navigation system that has been generalized for implementation in on-orbit space situational awareness missions in all relevant Earth orbit regimes. The relative motion is parameterized using a relative orbital element description which captures effects of the relevant perturbations in each orbital environment. Within the filter, these perturbation-induced trends are synthesized into observability-improving features that enable effective estimation of the relative motion using camera-based bearing measurements. All algorithms are verified in high-fidelity, hardware-in-the-loop simulation in preparation for eventual use in future distributed space system missions.

**11:40** **AAS 18-477** **LASER RANGING TO UNKNOWN OBJECTS FOR INITIAL ORBIT DETERMINATION, A FEASIBILITY STUDY**

*Mark Psiaki, Virginia Tech*

Satellite laser ranging to objects without retro-reflectors is explored as a means of providing range and range-rate data for use in initial orbit determination. The goal of this work is to couple laser range data with optically derived angular data and eliminate the need for a radar. It develops signal processing algorithms that determine orbit when 20-40 true photons and 1200-1300 noise photons arrive during a tracking window. One example considers a LEO object with a radar cross-section of 0.5 m^2 at a distance of 1170 km. The system determines orbit to 7 m position and 0.3 m/sec velocity accuracy.

**Aug 20, 2018 Superior B – Attitude Dynamics & Control – I**

## Monday Session 5 Attitude Dynamics & Control-I

Chair: Andrew J. Sinclair, Air Force Research Laboratory
Co-Chair: Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)

**13:30** **AAS 18-222** **Change of Inertia Tensor Due to a Severed Radial Boom for Spinning Spacecraft**

*Joseph E. Sedlak, a.i. solutions, Inc.; Babak Vint, a.i. solutions, Inc.*

Many spinning spacecraft include booms for plasma and fields instrumentation. Radial wire booms often have low mass but contribute significantly to the moment of inertia due to their length. Historically, there are cases where wire booms have been severed by micrometeoroid or debris impact. This paper investigates how to locate a boom break by finding the functional dependence of the inertia tensor on this location and relating it to measured changes in the coning angle. This new inertia tensor model will be included in the Magnetospheric Multiscale (MMS) mission Attitude Ground System to provide support if such an event occurs.

**13:50** **AAS 18-302** **DISCRETE-TIME ITERATIVE LEARNING CONTROL FOR BILINEAR SYSTEMS**

*Bing Song, Columbia University; Minh Phan, Dartmouth College; Richard Longman, Columbia University*

Iterative learning control (ILC) reduces control system tracking error to the hardware reproducibility level, by adjusting the command each run based on error previous run data. It can be used in spacecraft fine pointing sensors doing repeated scanning maneuvers. ILC for nonlinear systems is not well developed. This paper develops ILC laws for nonlinear systems based on Carleman bilinearized models. The ILC algorithms based on the bilinearized model converges faster when compared to its corresponding method based on a linearized model. Homotopy of desired trajectories outside the convergence region can be applied to learn to follow these trajectories.

**14:10** **AAS 18-315** **ON THE EXTREME BEHAVIOR OF THE SIMPLEST FORM OF ITERATIVE LEARNING CONTROL**

*Morgan Walker, Columbia University; Xiaoqiang Ji, Columbia University MC4703 ; Richard Longman, Columbia University*

The simplest form of iterative learning control (ILC) seeks to converge to zero tracking error of a tracking problem that is repeated. If the error in the previous run was 2 units too low, it asks for 2 more units in the current command. This algorithm is mathematically proved to converge to zero tracking error, but it exhibits unexpected behavior in applications. In simulations it can exhibit ridiculously large transients, and in addition, one can obtain different behaviors when simulating mathematically equivalent equations. These phenomena are studied in detail. They demonstrate the limitations of simulations in predicting real world behavior.

**14:30** **AAS 18-331** **A hybrid optimal control method for Time-Optimal Slewing Maneuvers of Flexible Spacecraft**

*Sandeep Singh, Texas A&M University, College Station, TX; Ehsan Taheri, Texas A&M University; John L. Junkins, Texas A&M University*

The problem of time-optimal, rest-to-rest slewing of a flexible spacecraft through a large angle is studied. These maneuvers are known to have bang-bang control profiles, which lead to undesirable excitation of higher frequency vibrations. The dynamics are usually approximated using the assumed modes method; and the resulting optimal control problem solved using both direct and indirect methods. In order to improve solution convergence, torque smoothing is applied through a novel hyperbolic tangent smoothing, demonstrated within indirect formulation. Results of these approaches are compared and advantages of smoothing, truncation of the discretized model and development of a hybrid optimal control method is discussed.

**14:50** **AAS 18-346** **Observer-Based Attitude Control with Measurement Uncertainties**

*Haichao Gui, Beihang University; Qingqing Dang, Beihang University*

Substantial feedback control laws have been designed using various methods in the past decades by assuming that a separation principle with the state estimation scheme to be utilized. This assumption, however, lacks rigorous proof. The equations of spacecraft attitude motion are nonlinear and it is well known that there exists no general separation principle for nonlinear systems. This paper shows that the classical quaternion PD controller actually enjoys a separation principle with a large class of attitude observers even in the presence of measurement uncertainties, a striking property that has never been revealed before. Instrumental in our approach is a

**15:10 Break**

**15:30 AAS 18-359 Optimal Motion Planning in Attitude Maneuver Using Non-Holonomic Turns for a Transformable Spacecraft**

*Kaoru Ohashi, The University of Tokyo; Toshihiro Chujo, JAXA/ISAS; Junichiro Kawaguchi, JAXA*

An innovative transformable spacecraft is studied in JAXA. One of the most innovative points of the spacecraft is that it is capable of the non-holonomic rotation for attitude maneuver. By the combination of non-holonomic rotations, the spacecraft can change its attitude largely without using fuel nor external forces/torques. In this research, we first show that it is expected that any kinds of attitude can be achieved in principle using a simple model, although it may not be optimal. After that, an idea of optimal motion planning in the maneuver is proposed.

**15:50 AAS 18-367 Disturbance-based Adaptive High-Order Sliding Mode Control for Spacecraft High Accuracy Pointing**

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

In this paper a disturbance-based adaptive high-order sliding mode scheme is applied to solve the challenging spacecraft attitude control problem, which involves simultaneously tackling nonlinearities of the governing equations and providing robustness towards unexpected external disturbances and varying initial conditions. This controller enables large-angle slews (tracking and regulation) exhibiting global stability all the while meeting high accuracy pointing for a space-telescopic mission named Infrared Astronomy Satellite Swarm Interferometer (IRASSI). It precludes the inherent chattering problem in classical sliding mode control (SMC), provides better transient response, faster manuever settling times and better accuracy as compared to SMC.

**16:10 AAS 18-387 ATTITUDE DETERMINATION OF ROTATING SPACECRAFT USING LIGHT CURVE MEASUREMENTS FROM MULTIPLE OBSERVATION SITES**

*Arun Bernard, Utah State University; David Geller, Utah State University*

The focus of this paper is to investigate the effects on the accuracy of the attitude estimate of a spacecraft that can be obtained when light curve measurements from multiple observation sites are combined. Simulations using a variety of different shape models, attitude dynamics, and observatory locations are used to determine the best conditions for satellite attitude determination. Attitude estimation is performed using a bootstrap particle filter, an unscented Kalman filter, and a modified extended Kalman filter are used to estimate the attitude of the spacecraft. A comparison of these three different estimation methods is also presented

**16:50** **AAS 18-469** **ROBUST AND OPTIMAL RULE-BASED ATTITUDE CONTROL OF SPACECRAFT WITH PARTIALLY-FILLED TANKS**

*Lilit Mazmanyan, Santa Clara University; Mohammad A. Ayoubi, Santa Clara University*

We present a robust-optimal fuzzy controller to stabilize the attitude of the spacecraft with a partially-filled fuel tank. First, the nonlinear equations of motion of spacecraft containing a liquid fuel store are presented briefly and approximated by the Takagi-Sugeno (T-S) fuzzy model. Next, the robust-optimal controller is designed with the parallel distributed compensation control technique. The problem of designing robust-optimal controller based on the Takagi-Sugeno fuzzy model with quadratic cost function and actuator amplitude constraint is cast in the form of linear matrix inequalities. In the end, the performance of the proposed fuzzy controller is examined with numerical simulation.

**Aug 20, 2018 Superior A – Spacecraft GNC – I**

**Monday Session 6 Spacecraft GNC-I**

Chair: John Christian, Rensselaer Polytechnic Institute
Co-Chair: Roberto Furfaro, The University of Arizona

**13:30** **AAS 18-226** **The Evolution of Deep Space Navigation: 2006-2009**

*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 fifth in a chronological sequence dealing with the evolution of deep space navigation and covers the time interval 2006 to 2009. 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 14 planetary missions.

| | | |
|---|---|---|
| **13:50** | **AAS 18-230** | **Theory of Connections Applied to First-Order System of Ordinary Differential Equations Subject to Component Constraints** <br> *Daniele Mortari, Texas A&M University; Roberto Furfaro, The University of Arizona* |

Motiivated by a class of first order differential equations generated by some optimal control problems this paper provides, using the methodology introduced by the Theory of Connections, least-squares solutions of first-order vectorial differential equations subject to linear constraints on the vector's components. This paper solves all different cases occurring in 2×2 time-varying systems with forcing term. Then, it shows how to build the constrained expressions for a 4×4 system generated by simple optimal control problem and for a generic 3×3 differential equation (with time-variant dynamical matrix and forcing term) subject to relative and integral constraints of the vector components.

| | | |
|---|---|---|
| **14:10** | **AAS 18-273** | **LINEAR DIFFERENTIAL EQUATIONS SUBJECT TO RELATIVE AND/OR INTEGRAL CONSTRAINTS** <br> *Hunter Johnston, Texas A&M University; Daniele Mortari, Texas A&M University* |

In aerospace engineering there is often the need to search solutions characterized by relative or integral constraints. One example is making the initial and final positions coincident, independent of the actual values of the positions and in other applications some quantity must be preserved, such as energy or volume, which requires the solution satisfy an integral constraint. This study details a *least-squares* method to solve relative and integral constraints for ordinary linear differential equations. In all numerical examples, ToC produces a solution at machine level precision and with two orders of magnitude faster solution time compared to the Chebfun toolbox.

| | | |
|---|---|---|
| **14:30** | **AAS 18-353** | **Assessment of a filter-based approach for autonomous relative positioning in space** <br> *Mathias Philips-Blum, Universität der Bundeswehr München; Luisa Buinhas, Institute of Space Technology & Space Applications; Kathrin Frankl; Thomas Pany, Universität der Bundeswehr München; Bernd Eissfeller* |

The mission concept IRASSI is composed of five free-flying spacecraft orbiting the Sun-Earth/Moon second Lagrange point, L2. Each spacecraft is equipped by an interferometry-based telescope to observe particular regions of the sky. For the observation a resolution of 0.1 arcsec is needed. To achieve such granular resolution magnitudes, the baselines (i.e. physical separation) between each pair of telescopes must be known with an accuracy of 5 μm. To achieve this accuracy some approaches have been developed and compared to solve this optimization problem.

| | | |
|---|---|---|
| **14:50** | **AAS 18-358** | **Prescribed performance control strategies for Halo orbit spacecraft rendezvous** <br> *Dandan Zheng; Jianjun Luo; Caisheng Wei, Northwestern Polytechnical University; RENYONG ZHANG, Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences* |

This paper studies finite-time libartion point orbit autonomous rendezvous for spacecraft with external disturbances and velocity-free during the terminal phase. The proposed method is essentially a compound control method, which consists of a novel prescribed performance control (NPPC) and integral-chain differentiator observer (ICDO) methodology. The ICDO is used to estimate the unknown relative velocity information , while rigorous proof show that the relative position and its rate can reach a small compacted region around zero within predefined time. Simulation results of a final closing rendezvous example are provided to demonstrate the effectiveness and robustness of the proposed composite ICDO-NPPC guidance approach.

**15:10 Break**

**15:30 AAS 18-362 Least-Square Solution of a Class of Optimal Space Guidance Problems via Theory of Connections**

*Roberto Furfaro, The University of Arizona; Daniele Mortari, Texas A&M University*

In this paper, we apply a newly developed method to solve boundary value problems for differential equations to solve optimal space guidance problems in a fast and accurate fashion. The method relies on the least-square solution of differential equations via orthogonal polynomial expansion and constrained expression as derived via Theory of Connection

**15:50 AAS 18-414 Monte Carlo Methods and Skewed Kalman Filters for State Determination**

*Louis Tonc, Department of Mechanical and Aerospace Engineering, Utah State University; David Geller, Utah State University; Geordie Richards, Department of Mechanical and Aerospace Engineering, Utah State University*

We will design and implement a skewed Unscented Kalman Filter for tracking orbital objects and debris in geostationary orbit (GEO) using ground and space-based observations, which could alleviate burden on current tracking systems. Under reasonable orbital conditions, the Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) both diverge after several updates from optical measurements. Monte Carlo methods can avoid this problem, but the computational burden is higher than for Kalman filters. We will implement a skewed Unscented Kalman Filter, which uses a closed skew normal distribution for tracking GEO objects, in order to avoid divergence at a reduced cost.

**16:10 AAS 18-419 The Cislunar Autonomous Positioning System**

*Jeff Parker, CCAR/Advanced Space, LLC; Bradley Cheetham, Advanced Space*

The Cislunar Autonomous Positioning System (CAPS) is a peer-to-peer autonomous, navigation solution that is self-sustaining, scalable, and evolvable. CAPS represents a high-impact technology with the potential to improve the frequency and accuracy of navigation solutions for cislunar missions. CAPS addresses the required spacecraft navigation need by providing onboard, autonomous position and velocity solutions derived from inter-spacecraft measurements while minimizing the need for ground support. CAPS can dramatically improve the viability of cislunar operations by reducing the use of limited and expensive ground-tracking resources, thus reducing operational costs and improving position accuracy and timeliness relative to current ground-based approaches.

**16:30 AAS 18-463 Normal Mode Attitude Determination and Control of ACADS: A Nano Class Earth Orbiter**

*Karthic Balasubramanian, Team Indus-Axiom Research Labs Private Limited*

The Axiom Capability Demonstration Satellite (ACADS) is a 10kg class Low Earth orbital demonstrator developed by Axiom Research Labs Private Limited. The objective is to design an Attitude Determination and Control System (ADCS) which provides the ACADS with attitude knowledge of 0.5 deg to meet the overall pointing requirement during the normal Earth pointing mode. The estimator incorporates measurements from Two-Axis Sun Sensor (TASS), Three Axis Magnetometer (TAM) and Gyroscopes and the attitude control is provided by Magnetic Torque Bars (MTBs). The attitude control is performed by the three Reaction wheels arranged in an orthogonal configuration.

**16:50 AAS 18-476 A SIX DEGREE-OF-FREEDOM SPACECRAFT DYNAMICS SIMULATOR FOR FORMATION CONTROL RESEARCH**

*Yashwanth kumar Nakka, Caltech; Rebecca Foust, University of Illinois at Urbana-Champaign; Sorina Lupu Elena, Caltech; Jui-Hung Sun, Caltech; Soon-Jo Chung, Associate Professor of Aerospace and Bren Scholar; JPL Research Scientist, Caltech*

This paper presents the design of a 6DOF spacecraft dynamics simulator for spacecraft formation control research at Caltech's Aerospace Robotics and Controls Group. The floating test bed simulates 5DOF dynamic motion and kinematic motion along the gravity direction using a linear actuator. The nonlinear dynamic model of the 6DOF simulator, a nonlinear control law to achieve trajectory tracking is presented which forms the core for future formation control research conducted in our lab.

**17:10 AAS 18-483 Robust Multi-star Measurement Weighting Technique for Tightly-coupled Stellar Aided Inertial Navigation System of Mars Exploration Rovers**

*Taeyoung Kim, Korea Advanced Institute of Science and Technology (KAIST) ; Hyochoong Bang, Korea Advanced Institute of Science and Technology (KAIST)*

A robust tightly-coupled SDINS/star sensor integrated navigation algorithm based on multi-star measurement weighting technique is proposed in this paper. To evaluate the error level of each multi-star observation, measurement quality factors based on single sensor parity space approach are introduced. In other words, the weight of each star measurement is independently determined according to its measurement noise level, and those weights are independently reflected in the calculation of the adaptive Kalman filter gain. Therefore, the improved performance of the tightly-coupled integration algorithm is achieved in various error conditions in terms of navigation accuracy and reliability.

## Aug 20, 2018 Maybird – Asteroid and Non Earth Orbiting Missions – I

## Monday Session 7 Asteroid and Non Earth Orbiting Missions-I

Chair: Angela Bowes, NASA LaRC
Co-Chair: Mar Vaquero, Jet Propulsion Laboratory

**13:30 AAS 18-221 Low-energy capture of asteroids for the logistic support of future Mars missions**

*Minghu Tan, School of Engineering, University of Glasgow; Colin McInnes, University of Glasgow; Matteo Ceriotti, University of Glasgow*

Capturing asteroids at the Sun-Mars $L_1/L_2$ libration points may be of significant benefit for future Mars missions. It is assumed that the candidate asteroid leaves its heliocentric orbit with a first maneuver. Then, with a second maneuver, the asteroid is inserted onto the stable manifold in the Sun-Mars system. Therefore, the entire transfer trajectory can be designed by patching together the Sun-centered two-body problem and the stable manifold in the Sun-Mars system. The methodology will then be used to search for candidate asteroids which can be captured at the Sun-Mars $L_1/L_2$ libration points with low energy.

**13:50 AAS 18-225 SmallSat Swarm Gravimetry: Revealing the Interior Structure of Asteroids and Comets**

*William Ledbetter, University of Alabama; Rohan Sood, University of Alabama; James Tuttle, Division of Geological and Planetary Sciences, California Institute of Technology*

Exploratory missions to small, unknown celestial bodies are limited in their ability to adequately characterize and investigate the resource potential of a body of interest. Driven by both scientific exploration and economic interest, the proposed strategy utilizes a swarm of SmallSats to deduce the internal structure of such bodies, enabling resource investigation. A multi-vehicle approach will significantly enhance the quality of data and will assist in close-proximity navigation. Preliminary work has validated the algorithms for density recovery, and current investigations are finalizing gravity recovery methods.

**14:10 AAS 18-232 Linearized Relative Orbital Motion Dynamics in a Rotating Second Degree and Order Gravity Field**

*Ethan Burnett, University of Arizona; Eric Butcher, University of Arizona*

A new linearized time-varying ODE model is introduced for spacecraft relative motion in a rotating second degree and order gravity field. The model is stand-alone and does not require integration of the chief orbit, but is restricted for use with near-circular chief orbits. Previous models have considered the effect of $C_{20}$ alone, as well as additional zonal harmonics. However, the addition of $C_{22}$ introduces additional time-varying dynamical effects due to the rotation of the primary body. Numerical simulations show that the newly obtained linearized model successfully captures these effects.

**14:30 AAS 18-239 Immersion-and Invariance-Based Adaptive Control of Asteroid-Orbiting and - Hovering Spacecraft**

*Keum Lee, CatholicKwandong Univ; Sahjendra Singh, University of Nevada Las Vegas*

The development of an immersion-and invariance-based adaptive state variable feedback control law for the closed orbit and hovering control of spacecraft in the vicinity of asteroids is the subject of this paper. The celestial body is assumed to be rotating with constant angular velocity about a fixed axis. Also, it is assumed that the mass and moments of inertia matrix of the asteroid, and the mass of the spacecraft are not known. The objective is to control the orbit of the spacecraft despite uncertainties in the system parameters. Based on the immersion and invariance theory, a noncertainty-equivalence

**14:50 AAS 18-279 Search for Stable Orbits Around the Asteroid 1999 KW4**

*Antonio Fernando Bertachini Prado, INPE; Thais Oliveira, INPE - National Institute For Space Research*

The goal of the present paper is to study the orbital motion of a space vehicle that orbits a particular binary system of asteroids, the system 1999 KW4. The model used is the ”restricted full body problem”, where the word ”restricted” is due to the fact that the mass of one of the bodies is negligible (the spacecraft) and the word ”full” means that the irregular shape of the asteroids that compose the system are considered. In particular, this paper search for stable orbits and zero velocity curves for a spacecraft that is orbiting the binary system NEA 1999 KW4.

**15:10 Break**

**15:30 AAS 18-295 Spacecraft Six Degree of Freedom Output Feedback Control Based on Dual Quaternion**

*Qingqing Dang, Beihang University; Haichao Gui, Beihang University; Shijie Xu, Beihang University*

This paper investigates the velocity-free spacecraft pose tracking control in terms of dual quaternions. First, a coupled linear velocity and angular velocity observer, driven by the position and attitude measurements, is designed via the immersion and invariance (I&I) methodology. After dominating the cross terms in the pose dynamics induced by angular velocity by high-gain injection, the observer is shown to be exponentially convergent. An output-feedback pose tracking law is then derived by combining the proposed velocity observer and a full-state feedback proportional-derivative controller with proven separation principle. Finally, an asteroid hovering operation is simulated to demonstrate its effectiveness and application.

**15:50 AAS 18-319 Real Time Adaptive Shape Reconstruction for Asteroid Landing**

*Shankar Kulumani, George Washington University; Taeyoung Lee, George Washington University*

Knowledge of the shape of an asteroid is crucial for spacecraft operations. The standard method of determining the gravitational potential, through the use of a polyhedron potential model, is dependent on the shape model. Furthermore, accurate landing or low altitude operations requires accurate knowledge of the surface topology. The typical approach to shape determination requires an extensive ``mapping" phase of the mission over which extensive measurements are collected and transmitted for Earth-based processing. Instead, we present an efficient method for estimating the shape of an asteroid in real time.

**16:10 AAS 18-320 Perturbation maps for a spacecraft around the near-Earth Asteroid (153591) 2001 SN263**

*Diogo Sanchez, National Institute for Space Research - INPE; Antonio Fernando Bertachini Prado, INPE*

The ASTER mission is the first Brazilian deep space mission. The target is the triple near-Earth Asteroid 2001NS$_{263}$. In this work we use the method of the integral of the disturbing accelerations to generate perturbation maps of this system. These maps are used to find less disturbed regions in this asteroid system, and to provide the fuel consumption, in terms of delta-v, to keep a spacecraft as close as possible to a Keplerian orbit. The results of this work can be used for the planning of the ASTER mission.

**16:30 AAS 18-375 SRP-based orbit control with application to small body landing**

*Kenshiro Oguri, University of Colorado Boulder; Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)*

With appropriate control algorithms, solar radiation pressure (SRP) can be effectively utilized as a source of orbit control force around asteroids. This paper develops an optimal control law for the SRP-based orbit control and demonstrates its effectiveness with numerical simulations on an asteroid landing scenario, which is inspired by a future small body exploration concept supported by NASA Innovative Advanced Concept (NIAC) program. The simulation results show the robustness of the control algorithms against possible disturbances, including the solar gravity, the irregular gravity field of the primary, and stochastic acceleration that can represent uncertainties in the dynamics modeling.

**16:50 AAS 18-448 Autonomous Swarming for Simultaneous Navigation and Asteroid Characterization**

*Nathan Stacey, Stanford University; Simone Damico, Stanford University*

This paper describes a novel measurement and estimation architecture to simultaneously navigate and estimate an asteroid's attitude, gravity field, and shape online. An autonomous swarm composed of a single main spacecraft and multiple nanosatellites in closed orbits about an asteroid take inter-satellite radiometric measurements while cooperatively tracking asteroid landmarks with optical sensors. This reconfigurable swarm offers stereovision capabilities and more geometrically diverse measurements than a single monolithic spacecraft. All spacecraft measurements are combined in an unscented Kalman filter (UKF). The UKF computation time is significantly reduced by exploiting the triangular structure in the matrix square root.

**17:10 AAS 18-484 END OF THE ROAD: THE TESLA ROADSTER AS A KINETIC IMPACTOR FOR BINARY ASTEROID DEFLECTION**

*Thais Oliveira, INPE - National Institute For Space Research*

In this paper, we study the mechanics of deflecting binary asteroids in the context of a particular case study. We utilize a version of the orbit of binary asteroid 65803 Didymos (1996 GT), which is the target of the AIDA mission. Our version of the Didymos orbit is modified such that our fictitious simulated version of Didymos collides with Earth. We then calculate optimized hypothetical maneuvers applied to the Tesla Roadster launched by the Falcon Heavy launch vehicle, that cause the roadster to intercept our fictitious binary asteroid in a manner that prevents a collision with Earth.

**Aug 20, 2018 Cirque – Orbital Debris**

## Monday Session 8 Orbital Debris

Chair: John H. Seago, ERC
Co-Chair: William Todd Cerven, Aerospace Corporation

**13:30** **AAS 18-338** **PRACTICAL SURVEY STRATEGIES FOR GEO FROM A SINGLE GROUND BASED OBSERVATORY**

*Akhter Mahmud Nafi, Utah State University; David Geller, Utah State University*

It is important to have the capability to detect GEO objects and update the GEO catalog on a regular basis to ensure the safety of high-value assets in this congested orbit regime. Thus, it is also important to develop and evaluate ground-based optical survey designs to help achieve these objectives. The GEO resident space object (RSO) environment and the observation properties of GEO RSO orbits from an Earth-based observatory are studied thoroughly. Based on this information, efficient and practical surveys will be designed for USU's Space Situational Awareness Telescope for Astrodynamics Research (USU-STAR).

**13:50** **AAS 18-382** **Frequencies of oscillation of a space tether towing space debris**

*Arun K. Misra, McGill University; Richa Saynak, McGill University*

One of the potential applications of tethers in space in the near term is the towing of space debris for its disposal. These systems are expected to have a nominal configuration inclined to the vertical, in fact almost horizontal, and will be subjected to a thrust for orbital transfer. The frequencies of libration, as well as of elastic longitudinal and transverse oscillations of these systems are determined for various system parameters. It is noted that these frequencies can be very different from those for the conventional tethered satellite systems in nominal vertical configurations.

**14:30** **AAS 18-352** **Characterizing the Reentry Prediction Uncertainty of Tiangong-1**

*Eric Eiler, Aerospace Corporation; Andrew Abraham, Lehigh University*

In March 2016, the Tiangong-1 Chinese space station ended its telemetry service and became uncontrolled space debris. This large space object, with an orbit that never rose above 400 km, was predicted to reenter between late 2017 and mid 2018 with a significant reentry prediction uncertainty that spanned several months. Between April 2017 and April 2018, Tiangong-1's 2018 reentry, a study was conducted to better evaluate the uncertainty in reentry prediction of the Tiangong-1 spacecraft and found that the traditional ±20% time-to-go rule-of-thumb was insufficient to accurately capture this uncertainty. Here, a process is described to better characterize this uncertainty.

**14:50 AAS 18-372 Targeting Regions of Chaos In the GNSS Regime**

*Marielle Pellegrino, University of Colorado Boulder; Daniel Scheeres, University of Colorado at Boulder*

This paper seeks to utilize solar radiation pressure in the form of a solar sail to reach regions of chaos proximate to GNSS satellite orbits for debris mitigation purposes. These regions are caused by luni-solar resonances and are defined by the semimajor axis, eccentricity and inclination. The semimajor axis is defined by the orbit the satellite is in, (GPS, Galileo, GLONASS, and Beidou) but the eccentricity and inclination will need to change from the initial orbit. This paper explores the minimum sail characteristics needed to achieve these orbits.

**15:10 Break**

**15:30 AAS 18-394 Long Short-Term Memory Neural Networks for the Prediction of Localized Atmospheric Density for Orbit Determination**

*Kyri Barton, The University of Kansas; Craig McLaughlin, University of Kansas Aerospace Engineering*

Atmospheric density presents the largest uncertainties in the estimation of drag on satellites in Low Earth Orbit. This research uses Long-Short-Term-Memory neural networks to improve neutral density estimation along the orbit of the CHAllenging Minisatellite Payload (CHAMP) satellite. Preliminary comparisons with the accelerometer data over the future specified time horizon reveals more accurate density estimation and prediction using the presented neural networks than the existing empirical atmospheric models. As expected, the accuracy decreases for a longer prediction time interval in all cases. The network-estimated neutral densities are found to substantially reduce the orbit propagation error.

**15:50 AAS 18-418 Uncertainty in Drag Coefficient Modeling and the Effects on Density Estimation**

*Craig McLaughlin, University of Kansas Aerospace Engineering; Alex Sizemore, University of Kansas; Piyush Mehta, West Virginia University*

Various satellite drag coefficient theories are examined to better characterize the uncertainties of drag coefficients used in orbit analysis. The drag coefficient theories for spherical satellites are applied to the Atmospheric Neutral Density Experiment (ANDE) series of satellites. The different drag coefficients are then used in an orbit estimation process that also estimates atmospheric neutral density along the satellite orbit. The effects on density estimation of the different theories and various temporal cadence of drag coefficient updates are quantified.

**16:10** **AAS 18-430** **Analysis of a Threshold on Long-Term Orbital Collision Probability**

*Alan B. Jenkin, Aerospace Corporation; John McVey; Glenn Peterson, Aerospace Corporation*

U.S. standards on limiting orbital debris contain a threshold on long-term collision probability between mission orbital objects and background orbital objects larger than 10 cm. An analysis was performed to determine how often this threshold may be exceeded and whether it is consistent with recommended end-of-life disposal practice in U.S. and international debris mitigation guidelines. Collision probabilities were determined for a set of future launched objects and processed to determine the percentage of objects contained by the threshold and the variation in total mean number of collisions for the set of objects processed as the threshold is varied.

**16:30** **AAS 18-438** **Uncertainty Quantification Using Non-Intrusive Generalized Polynomial Chaos Expansion for Orbital Debris Studies**

*Rajnish Bhusal, The University of Texas at Arlington; Kamesh Subbarao, University of Texas at Arlington*

This paper demonstrates the use of generalized polynomial chaos expansion for propagation of uncertainties present in various dynamical models. The idea behind generalized polynomial chaos is to express the random solutions to stochastic differential equations as orthogonal polynomials of input random variables. In this paper, a sampling based non-intrusive approach using pseudospectral stochastic collocation is employed to obtain the coefficients required for the generalized polynomial chaos expansion. This paper illustrates the efficacy of various recently developed quadrature techniques within the generalized polynomial chaos expansion framework.

**16:50** **AAS 18-376** **Disposal design for geosynchronous satellites revisited**

*Ioannis Gkolias, Politecnico di Milano; Camilla Colombo, Politecnico di Milano*

The orbits at geosynchronous altitude provide a valuable natural resource for the human kind. In the absence of atmospheric drag, human intervention is needed to keep the region clean of space debris. Current post-mission disposal guidelines deal efficiently with the geostationary low-inclination, low-eccentricity satellites but fail to efficiently regulate the whole region. In this work, we will revisit the problem of geosynchronous disposal orbits, trying to identify all possible mechanisms for designing effective disposal strategies. Massive numerical simulations are coupled with optimization techniques and semi-analytical modelling to achieve this goal.

# Tuesday August 21, 2018

### Aug 21, 2018 Superior A – Astrodynamics – II

**Tuesday Session 1 Astrodynamics-II**

Chair: Tarek Elgohary, University of Central Florida
Co-Chair: Aaron J. Rosengren, University of Arizona

**8:00** **AAS 18-233** **Comparison between First and Second-Order Gauss Variational Equations under Impulsive Control**

*Daniele Mortari, Texas A&M University; Gang Zhang, Harbin Institute of Technology*

Due to the insufficient 20 page limit, this paper shows, just as example, how to derive the second-order variation of the inclination under impulsive control and provides, under assigned impulsive velocity variation, the comparison between the orbital elements variations predicted by the first-order and second-order Gauss Variational Equations and the true variations. This is done through simulated Monte Carlo tests. The complete derivation of the classical and the nonsingular orbital elements variations is done in Ref. [1].

**8:20** **AAS 18-261** **POWERED AERO-GRAVITY ASSISTED MANEUVERS IN VENUS AND MARS CHANGING THE BANK ANGLE OF THE SPACECRAFT**

*Jhonathan Murcia Piñeros, INPE; Antonio Fernando Bertachini Prado, INPE*

In a three body system, with the Sun as massive body, a planet as secondary body and a spacecraft as a massless body. If the planet has atmosphere and the pericenter of the spacecraft is lower than the atmospheric limit, the aerodynamic forces affect the gravity-assist, and the new maneuver is known as aero-gravity assisted. Including an instantaneous impulse in the pericenter, it is created the powered aero-gravity-assisted maneuver. The present paper uses this type of maneuver considering Drag, Lift and the bank angle to control the Lift direction. With this maneuver, it is possible to make energy and inclination changes.

**8:40** **AAS 18-380** **STUDYING THE MOTION OF A SPACECRAFT ORBITING AN ASTEROID MODELED AS AN ASYMMETRIC MASS DIPOLE**

*Antonio Fernando Bertachini Prado, INPE; Diogo Sanchez, National Institute for Space Research - INPE; Leandro Brejão, INPE; Leonardo Torres, INPE*

The goal of the present paper is to derive the equations of motion for a negligible mass travelling around a double asteroid system where one body can be considered to be a rotating asymmetric mass dipole. Several aspects are studied, like the zero-velocity curves and the determination of the positions of the libration points. Depending on the values of the *Jacobian constant*, the boundary regions where the motion of the particle is allowed is determined. Next, it is verified the stability of these equilibrium points, including the collinear and non-collinear points.

**9:00** **AAS 18-413** **An Investigation of Natural Dynamical Processes on Asteroid Surfaces Using a Combined Asteroid Surface-Boulders Model**

*Daniel Brack, University of Colorado Boulder; Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)*

A new asteroid model is presented to investigate the interaction between the asteroid's rotational dynamics and the state of boulders on its surface. The model considers boulder motion on the surface of the asteroid as well as boulder launch, orbit and crash. These events effect the translational and rotational dynamics of the asteroid. Changing the angular velocity mostly by launch and crash events, but also by the changing moment of inertia. Rolling boulders tend to reach the equator and launch from it or rest near it. The resulting orbits are of low inclination and chaotic leading to crash events.

**9:20 AAS 18-474 FIRST ORDER APPROXIMATION OF THE EFFECTS OF SOLAR RADIATION PRESSURE ON RELATIVE MOTION USING A LINEARIZED REPRESENTATION OF RELATIVE ORBITAL ELEMENTS**

*Hermann Kaptui Sipowa, University of Colorado Boulder; Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)*

The relative motion of two spacecraft, flying in Chief-Deputy configuration, is analyzed under the perturbating force of Solar Radiation Pressure. Both the CannonBall Model and the Flat Plate Model are used in the analyis. A first order Taylor series approximation is used to characterized the dynamic of relative orbital elements, and thus approximate the relative position and velocity of the deputy. Finally, this work makes use of a Unit-Sphere Approach to map the approximated orbital elements on to the LVLH cartesian frame. The accuracy of the approximation is assessed for closed proximity operations, for spacecraft with similar and different dynamics.

**9:40 Break**

**10:00 AAS 18-205 Action-Angle Variables near Degenerate Periodic Orbits**

*William Wiesel, Air Force Institute of Technology*

Classical Floquet theory describes motion near a periodic orbit. However, there is a missing piece in the Floquet solution. A different Jordan normal form allows the decoupling of modal dynamics \it near \rm the periodic orbit, and not just \it on \rm the periodic orbit. A new eigenvector solution is offered in the case of repeated eigenvalues. This solution extends the Floquet decomposition to adjacent trajectories, and is fully canonical. Some numerical examples are offered.

**10:20 AAS 18-209 Trajectory Design Leveraging Low-Thrust, Multi-Body Equilibria and their Manifolds**

*Andrew Cox, Purdue University; Kathleen C. Howell, Purdue University; David Folta, NASA Goddard Space Flight Center*

A key challenge in low-thrust trajectory design is generating preliminary solutions that simultaneously specify the spacecraft position and velocity vectors, as well as the thrust history. To mitigate this difficulty, dynamical structures within a combined low-thrust circular restricted 3-body problem (CR3BP) are investigated as candidate solutions to seed initial low-thrust trajectory designs. The addition of low-thrust to the CR3BP modifies the locations and stability of the equilibria, offering novel geometries for mission applications. Transfers between these novel equilibria are constructed by leveraging the associated stable and unstable manifolds and insights from the low-thrust CR3BP.

**10:40** **AAS 18-224** **Fully-Coupled Spherical Pendulum Model to Simulate Spacecraft Propellant Slosh**

*Paolo Cappuccio, Sapienza University of Rome; Cody Allard, University of Colorado; Hanspeter Schaub, University of Colorado*

This paper presents the derivation of the equations of motion of a spacecraft undergoing a general three-dimensional tumble affected by propellant sloshing disturbances. A spherical pendulum model is used for simulating this phenomenon because it can better represent the sloshing behavior for rotational dynamics in micro-gravity. This general formulation permits the use of as many pendulums as necessary to approximate the actual sloshing behavior. The model is implemented and verified using energy and momentum conservation in the Basilisk astrodynamics software package and simulation examples and verification plots are included in this paper.

**11:00** **AAS 18-309** **Data-Driven Framework for Real-time Thermospheric Density Estimation**

*Piyush Mehta, West Virginia University; Richard Linares, University of Minnesota*

In this paper, we demonstrate a new data-driven framework for real-time density estimation via data assimilation in physical ionosphere-thermosphere models. The framework has two main components: (i) the development of a quasi-physical dynamic reduced order model (ROM) that uses a linear approximation of the underlying dynamics and effect of the drivers, and (ii) data assimilation and calibration of the ROM through estimation of the ROM coefficients that represent the model parameters. The framework is a first of its kind, simple yet robust and accurate method with high potential for providing real-time operational updates to the state of the upper atmosphere.

**11:20** **AAS 18-400** **Multi-Sphere Method for Flexible Conducting Space Objects: Modeling and Experiments**

*Jordan Maxwell, CU Boulder; Hanspeter Schaub, University of Colorado; Kieran Wilson, University of Colorado Boulder*

The need for faster-than-realtime modeling of the electrostatic forces and torques to support new categories of missions has led to development of the Multi-Sphere Method (MSM) in which complex geometries are replaced with a set of conducting spheres. This investigation applies MSM to flexible materials, unlike previous work which assumed a rigid structure. Experiments in which a thin flexible conductor is deformed by an electric field are compared with an MSM model. Results indicate that MSM can predict the positions of all parts of a 6cm strip to well within 1cm.

**11:40** **AAS 18-345** **Coverage optimization for Satellite Constellations**

*Alain LAMY, CNES*

The paper presents methods for the definition of satellite constellations that optimize coverage and revisit time. The methods were first used in the context of the improvement of altimetry services by a better time and space coverage of the Earth (or rather ocean) surface, but have since then been used for other applications. The paper will show the coverage criterion used, various results found for homogenous or heterogeneous constellations (in particular when the objective is to extend existing constellations), and results of analyses aiming at better understanding the type of constellation that has to be looked for.

**Aug 21, 2018 Maybird – Trajectory Design & Optimization – II**

**Tuesday Session 2 Trajectory Design & Optimization-II**

Chair: Nathan Strange, Jet Propulsion Laboratory / California Institute of Technology
Co-Chair: Angela Bowes, NASA LaRC

**8:00** **AAS 18-243** **Design of Interplanetary Trajectories with Multiple Synergetic Gravitational Assist Maneuvers via Particle Swarm Optimization**

*Matthew Shaw, Pennsylvania State University; Robert G. Melton, Pennsylvania State University*

The design capacity for synergetic gravity assists changes possible types of optimal interplanetary trajectories. The application of Particle Swarm Optimization (PSO) is used to determine optimal mission trajectories from Earth to planets of interest, via synergetic gravity assist maneuvers. In order to verify the design results from PSO, past missions (Voyager 1, Voyager 2, and Cassini) are re-examined from a new design perspective before a new mission design to Saturn is considered. The computation of these solutions offers the significant benefit of costing one to two minutes of wall-clock time with standard desktop or laptop computing systems.

**9:00** **AAS 18-310** **Two-Body Orbital Boundary Value Problems with Constraints in Regularized Coordinates**

*Bharat Mahajan, Odyssey Space Research; Rao S. Vadali, Texas A&M University*

The Lambert problem is widely used in the mission design and optimization. In preliminary mission design, it is often necessary to generate trajectory legs that satisfy mission constraints in order to have a good initial guess for analysis as well as for further optimization. In this work, various two-body orbital boundary value problems with constraints on velocities, flight path angle, Delta-v, transfer angle, etc., are studied, and their exact solutions in universal form are derived using KS-transformation. These solutions have potential applications in fast trajectory design by reducing the need to iterate on intermediate solutions to satisfy mission constraints.

**9:20** **AAS 18-314** **Trajectory Design for a Solar Sail Mission to Asteroid 2016 HO3**

*Jeannette Heiligers, Delft University of Technology; Juan Fernandez, NASA Langley Research Center; Olive Stohlman, NASA Langley Research Center; Keats Wilkie, NASA Langley Research Center*

This paper presents the preliminary mission analysis for a solar-sail propelled CubeSat rendezvous mission with asteroid 2016 HO3, a quasi-satellite of Earth. For solar sail technology that is currently under development at NASA Langley Research Center, trajectories are found that take 2.2 - 4.2 years to complete, depending on the assumed sail reflectance model and spacecraft area-to-mass ratio. To demonstrate the superior performance of solar sail technology for this mission, fuel-optimal solar electric propulsion trajectories are also designed. These show longer transfer times and require a propellant consumption that exceeds the expected propellant capacity onboard the CubeSat.

**9:40** **Break**

**10:00** **AAS 18-324** **Mission Analysis for Earth to Mars-Phobos Distant Retrograde Orbits**

*Davide Conte, Pennsylvania State University; David B. Spencer, Pennsylvania State University*

This paper focuses on the trajectory design for LEO to Mars-Phobos DRO missions. Lunar DROs are also briefly explored as an alternative departure location. We present the methodology used to compute LEO to Mars-Phobos DRO trajectories and required launch C3, arrival v-inf, TOF, and total mission $\Delta V$. Results show that using propellant-optimal LEO to Mars-Phobos DRO trajectories, such DROs could be used as a staging location between Mars and Phobos. Assuming refueling is available at the targeted DRO, LEO-LMO trajectories would have higher overall mission $\Delta V$, but would have lower gear ratio thanks to the added "pit stop."

**10:20** **AAS 18-332** **Framework for Optimizing Many-Revolution Low-Thrust Transfers**

*Zubin Olikara, NASA Jet Propulsion Laboratory*

This work presents a general-purpose approach to directly optimize many-revolution low-thrust transfers around solar system bodies. Control parameterization combined with numerical averaging allows complete trajectories to be generated using a small number (tens) of control variables. A collocation discretization enables robust convergence while providing flexibility for a wide variety of constraints. The scheme is developed for both minimum-time and minimum-fuel (bang-bang) transfers and illustrated using a collection of test cases. Computational performance is competitive with indirect techniques while also being notably insensitive to initial guess.

**10:40** **AAS 18-337** **Event-Driven Space Logistics Network Optimization for Cislunar Supply Chain Design with High-Thrust and Low-Thrust Propulsion Technologies**

*Bindu Jagannatha, University of Illinois at Urbana-Champaign; Koki Ho, University of Illinois, Urbana-Champaign*

Various high-thrust and low-thrust propulsion technologies have been developed to achieve sustainable future space exploration campaigns; however, designing and optimizing a multi-mission campaign with both high-thrust and low-thrust propulsion technologies options are generally computationally challenging due to the coupled logistics design and orbital dynamics. To tackle this challenge, this paper develops a novel event-driven space logistics network approach with mixed-integer linear programming methods and precomputed orbital mechanics models for campaign-level space mission design. The specific case of optimally designing a cislunar propellant resupply chain is considered for the purposes of supporting lunar surface access.

**11:00** **AAS 18-341** **Solar Orbiter 2020 February Mission Profile**

*Jose Manuel Sanchez Perez, ESA; Waldemar Martens, ESA / ESOC; Gábor Varga, European Space Agency*

The ESA-NASA Solar Orbiter mission is devoted to study the heliosphere and its interdependency to solar activity. After programmatic delays the mission is currently set for launch in February 2020 in a trajectory using Earth and Venus gravity assists with a short 1.8-year. Science observations will be performed from Sun distances down to 0.28 AU, while the solar inclination will be gradually raised to reach 33 degrees by the end of the 10 year lifetime. The paper will provide an overview of the mission design including detailed trajectory timelines and profiles of the 2020 February baseline.

**11:20** **AAS 18-364** **Low-Thrust Stationkeeping for an Elliptical Polar Lunar Orbit**

*David Folta, NASA Goddard Space Flight Center; Alex Mazarr, Virginia Tech*

The Lunar IceCube mission, a partnership between NASA's Goddard Space Flight Center and Morehead State University, is set to launch aboard Exploration Mission-1 (EM-1). With a primary science objective to observed volatiles and water ice near the lunar equator, it requires a tightly controlled elliptical orbit. In order to achieve and maintain the required orbit parameters, a low thrust Busek BIT-3 ion thruster propulsion system is the only maneuver capability available. This paper discusses perturbations of the specific lunar orbit and operational low thrust stationkeeping concepts that extend the life of the mission while maintaining required orbit parameters.

**11:40** **AAS 18-215** **Optimal Nonlinear Feedback with Feedforward Control of High Speed Aerospace Vehicles Using a Spatial Statistical Approach**

*Christian Chilan, University of Illinois at Urbana-Champaign; Bruce Conway, Univ of IL; Brendan Bialy, Air Force Research Laboratory; Sharon Stockbridge, Air Force Research Laboratory*

This work describes the development and application of an alternative method for synthesizing optimal nonlinear feedback controllers from pre-computed open-loop optimal trajectories (i.e. extremals) that does not involve the second-order variations of the performance index. It is among the first applications in a dynamical system of a method known as kriging developed for (static) geostatistics problems. The kriging model is generated a priori and we have found that the feedback control synthesis takes just a few milliseconds on a personal computer. The method is applied to the real-time optimal control of a high speed aerospace vehicle.

**Aug 21, 2018 Superior B – Attitude Dynamics & Control – II**

**Tuesday Session 3 Attitude Dynamics & Control-II**

Chair: Kamesh Subbarao, University of Texas at Arlington
Co-Chair: Christopher Roscoe, Applied Defense Solutions

**8:00** **AAS 18-294** **Determination of Fault Point of Solar Panel Based on Photogrammetry**
*Hongwen Wang, Beihang University*

This article verifies the applicability and reliability of photogrammetry technology applied on the measurement of measuring points of solar panels, applies it on the determination and analysis of fault points, and successfully finds out the location of fault points to lay the foundation of the following strategy which is designed to adjust the optimal measuring points scheme.

**8:20** **AAS 18-303** **Model-Free Iterative Learning Control Using Reinforcement Learning**
*Bing Song, Columbia University; Minh Phan, Dartmouth College; Richard Longman, Columbia University*

Iterative learning control (ILC) tries to reach zero tracking error in hardware, following a repeated desired trajectory. It adjusts the current command based on error in the previous iteration. Spacecraft applications include fine pointing of sensors doing repeated scanning maneuvers. Reinforcement learning (RL) is similar but it simultaneously seeks to find an optimized trajectory. This paper compares and discusses the relationship in a control context. Previous work studied model predictive Q-Learning, connecting Q-Learning and Model Predictive Control. We use parallel thinking to address the ILC problem. Unlike usual ILC, the resulting ILC algorithm uses gains that are adjusted each iteration.

**8:40** **AAS 18-313** **On novel appointed-time inertia-free adaptive attitude control of spacecraft**
*Caisheng Wei, Northwestern Polytechnical University; Jianjun Luo*

This paper investigates a novel fixed-time attitude control scheme for a rigid spacecraft with unknown inertial properties and external disturbance. First, a new prescribed performance function is developed, based on which an adaptive inertia-free controller is constructed to guarantee the fixed-time convergence. Compared with the existing finite-time/fixed-time attitude controllers based on sliding mode control technique, the primary advantage is the fractional power state or output feedback is not used, while the arbitrarily appointed-time convergence and steady-state tracking accuracy can be simultaneously guaranteed. Finally, a group of illustrative examples are employed to validate the effectiveness of the proposed control scheme.

**9:00** **AAS 18-316** **Development and Laboratory Experimentation of a Magnetorquer Control System for CubeSat Using a Three-Axis Simulator**

*Guglielmo Cervettini, Magneti Marelli - Automotive Lighting / Politecnico di Torino; Hyeongjun Park, New Mexico State University; Dae Young Lee, Center for Space Research, University of Texas at Austin; Stefano Pastorelli, Politecnico di Torino; Marcello Romano, Naval Postgraduate School*

In this paper, a magnetorquer system is developed and tested for the attitude maneuver of a dynamic three-axis spacecraft simulator. The design and developing procedure is presented to perform ground testing regarding the main attitude control maneuvers that involve magnetic actuators on CubeSats. This paper reports several ground test scenarios and the comparison of the numerical simulatons and the experimental results on the air-bearing sapcecraft attitude test bed. The detumbling performance of the magnetorquer control system is clearly demonstrated by comparing with the case without the magnetorquer control.

**9:40** **Break**

**10:20** **AAS 18-333** **Equilibria Associated with the Attitude Dynamics of a Rigid Body in Keplerian Motion**

*Roshan Thomas Eapen, Texas A&M University; Manoranjan Majji, Texas A&M University, College Station; Kyle T. Alfriend, Texas A&M University*

This paper investigates the nonlinear attitude dynamics of a rigid body in a Keplerian orbit. Using Classical Rodrigues Parameters for the attitude motion of the rigid body subject to gravity-gradient torques enables us to characterize the rotational motion about its mass center. The stability of oscillations is investigated using inertia as a parameter and it is shown that large oscillations are induced due to the energy exchange between the pitching and roll-yaw motion of the rigid body. Furthermore, the effect of moments of inertia on the attitude motion is studied under the framework of a fourth-order gravity-gradient potential.

**10:40** **AAS 18-422** **Reorientation of rigid spacecraft using onboard convex optimization**

*Josep Virgili-Llop, Naval Postgraduate School; Alanna Sharp, U.S. Army ARDEC; Marcello Romano, Naval Postgraduate School*

A guidance algorithm for constrained attitude reorientation maneuvers suitable for onboard implementation and real-time use is presented. Using a sequential convex programming approach the proposed algorithm is able to find a locally optimal solution by sequentially solving inner convex approximations of the original guidance problem. Under mild conditions the algorithm is recursively feasible and strictly descending. The results of an implementation on an embedded computer are presented as evidence to support the algorithm's suitability for onboard implementation and real-time use. Finally, the solutions by the proposed algorithm are compared to the solutions obtained with pseudospectral methods and particle swarm optimization.

**11:20** **AAS 18-480** **Attitude Control of Spinning Solar Sails Based on Modal Analysis**

*Yuki Takao, The University of Tokyo; Shota Kikuchi, University of Tokyo; Osamu Mori, Japan Aerospace Exploration Agency; Junichiro Kawaguchi, JAXA*

Attitude dynamics and control of spinning solar sails are investigated considering the flexibility of sail membranes. Attitude maneuver of solar sails is, in many cases, performed using thrusters. In most studies, the attitude motion is analyzed assuming that the spacecraft is a rigid disk. However, the sail membrane deforms during attitude maneuver due to flexibility. This may cause coupled vibration between the spacecraft main body and sail membrane. This study presents an analysis model of spinning solar sail attitude dynamics considering sail deformation, based on modal analysis. Attitude control law is then shown using the analysis model developed.

**11:40** **AAS 18-305** **On the use of Basis Functions to Reduce the Control Dimension in Iterative Learning Control**

*Bowen Wang, Columbia University; Richard Longman, Columbia University*

Iterative learning control (ILC) aims for precise tracking of a repeated trajectory. Spacecraft applications include precision scanning motion of fine pointing equipment. The usual learning gain matrix can be very large. This paper addresses this issue by projecting onto basis functions. This is also a different way to address instability of the discrete time ILC inverse problem. The choice of basis functions must capture the system behavior during both steady state and transient portions of the desired trajectory. This paper studies ways to pick basis functions for effective ILC design.

## Aug 21, 2018 Cirque – Space Situational Awareness – II

### Tuesday Session 4 Space Situational Awareness-II

Chair: Islam Hussein, Applied Defense Solutions
Co-Chair: Rohan Sood, University of Alabama

**8:00** **AAS 18-220** **The Effect of Differential Color Refraction on Short-Arc Estimation of the Area-to-Mass Ratio of Geostationary Objects Using Ground-Based Telescopes**

*Roman Geykhman, Massachusetts Institute of Technology; Kerri Cahoy, Massachusetts Institute of Technology*

Ground-based telescopes collect the majority of astrometric observations of geosynchronous satellites and debris. Earth's atmosphere subjects this data to systematic bias from differential color refraction (DCR). Advancements in star catalog accuracy leave DCR as the dominant bias source in ground-based astrometry. We analyze the effect of DCR on short arc orbit estimation. We find that DCR bias is absorbed into a biased estimate of solar radiation pressure area-to-mass ratio and imposes an error floor of several tens of meters per day on resulting orbit predictions. We describe a spectroscopic instrument for DCR compensation and present preliminary measurements.

**8:20** **AAS 18-244** **HIGH FIDELITY COLLISION PROBABILITIES ESTIMATED USING BRUTE FORCE MONTE CARLO SIMULATIONS**

*Doyle Hall, Omitron, Inc.; Steve Casali, Omitron, Inc.; Lauren Johnson, Omitron; Brent Skrehart, Omitron, Inc.; Luis Baars, Omitron, Inc.*

The NASA Conjunction Assessment Risk Analysis team has implemented new software to estimate the probability of collision ($P_c$) for Earth-orbiting satellites. The algorithm employs a “brute force Monte Carlo” (BFMC) method which differs from most other methods because it uses orbital states and covariances propagated from their orbit determination epoch times using the full set of the Astrodynamics Support Workstation’s higher order theory models, including the High Accuracy Satellite Drag Model. This paper describes the BFMC algorithm, presents comparisons of BFMC $P_c$ estimates to those calculated using other methods, and discusses the implications for conjunction risk assessment.

**8:40** **AAS 18-272** **Effect of Cross-Correlation of Orbital Error on Probability of Collision Determination**

*Steve Casali, Omitron, Inc.; Doyle Hall, Omitron, Inc.; Dan Snow, Omitron Inc.; Matthew Hejduk, Astrorum Consulting LLC; Lauren Johnson, Omitron; Luis Baars, Omitron, Inc.; Brent Skrehart, Omitron, Inc.*

This paper discusses the effect of global model error on probability of collision (Pc) determination. Modifications to the Pc formulation for cross-correlation of orbital error in prediction are developed and assessed for recent conjunctions. While specific geometries can be identified or constructed to produce significant change in Pc for the modified formulation, it is of operational interest to quantify the relative occurrence of such cases for satellite conjunction risk assessment. Such analysis is feasible per data collections in place over the past year.

**9:00** **AAS 18-268** **Q-Learning Algorithm for Path-Planning to Maneuver through a Satellite Cluster**

*Xiaoyu Chu, Beijing Institute of Technology; Kyle T. Alfriend, Texas A&M University; Jingrui Zhang; Yao Zhang*

This study focuses on the path planning for diving through a satellite cluster. The objective is to rendezvous with the central satellite of the formation and avoid a collision with the other satellites in the formation. The dynamic configuration of the satellite cluster is first analyzed and the environment model is predicted. Then the theory of a reinforcement learning method, Q-learning, is introduced. According to the specific application, the reward function in learning is specified to guide the learning system quickly to success. Finally, the approaching mission is simulated and the paths avoiding the dynamic obstacles are generated after learning.

**9:20** **AAS 18-336** **Streak Detection and Characterization in Ground-Based Optical Observations of Space Objects**

*Nathan Houtz; Carolin Frueh, Purdue University*

Objects in Earth orbit create streaks in sidereally-tracked images with long exposure times. For the purpose of detecting and characterizing new or previously lost objects, the algorithms that detect such streaks cannot restrict their search by making assumptions about streaks' properties. Detecting and characterizing streaks of unknown parameters is challenging to do in a computationally efficient manner, since simple detection methods are not adequate to identify faint streaks. We present a method of streak detection and characterization that uses computationally-efficient thresholding for identifying objects, and fits image data with a mathematical streak model for accurate estimation of streak parameters.

**9:40** **Break**

**10:00** **AAS 18-347** **Early Blast Point Determination For Space Object Fragmentation Events**
*Weston Faber, Applied Defense Solutions*

As more and more objects are launched into space the potential for breakup events and space object collisions is ever increasing. These events create large clouds of debris that are extremely hazardous to space operations. Providing timely, accurate, and statistically meaningful Space Situational Awareness (SSA) data is crucial in order to protect assets and operations in space. Determining the point of initial breakup, the blast point, is valuable in order to characterize and model the event. In this paper, the authors present a technique to determine the blast point that takes into account the uncertainty in debris fragment state.

**10:20** **AAS 18-415** **Uncertainties in the conjunction risk assessment of the CYGNSS constellation.**
*Charles Bussy-Virat, University of Michigan; Aaron Ridley, University of Michigan*

Conjunction analysis is particularly challenging at altitudes below ~1,000 km, where drag is the largest perturbing force. Uncertainties in the atmospheric density result in important uncertainties in the probability of collision. However, current algorithms neglect these uncertainties and assume a perfect knowledge of the atmospheric density to compute the probability of collision. The Spacecraft Orbital Characterization Kit (SpOCK) is an orbit propagator that computes the probability of collision taking into account these uncertainties. It is used to investigate the effects of density uncertainties on actual conjunctions of the CYGNSS constellation, launched in December 2016.

**10:40** **AAS 18-439** **Assessing Measures to Reliably Predict Collisions in the Presence of Uncertainty**
*Alexander Burton, Purdue University; Carolin Frueh, Purdue University; Mitchell Zielinski, Purdue University*

Typical methods of computing the probability of collision between two satellites are heavily influenced by uncertainty in the objects' states. High uncertainty can lead to over-estimating the probability of collision, and the initiation of expensive and unnecessary avoidance maneuvers. This study explores the use of additional statistical parameters including Kullback-Leibler divergence, Mahalanobis distance, and Bhattacharyya distance in the analysis of conjunction events between spacecraft. It is hoped that analyzing the evolution of these parameters over time as the objects are observed will aid in collision prediction.

**11:00 AAS 18-446** **Conjunction Analysis and Probability of Collision Using Relative Orbital Elements**

*Christopher Shelton; John L. Junkins, Texas A&M University*

In this paper a set of relative orbital elements are presented along with conditions for collision between two spherical bodies in the relative orbital element space. Formulating the probability of collision problem in this coordinate system is shown to make the problem more linear as well as reduce computational burden. This new method is then used to compute the probability of collision and is compared, using the CRATER collision risk assessment tool, to results from the Cartesian formulation of the probability of collision integral and Monte Carlo results on a number of test cases.

**11:20 AAS 18-453** **LEO SSA at the SpOT Facility**

*Morgan Yost, Lockheed Martin; Andrew Zizzi, Lockheed Martin*

Lockheed Martin's Space Object Tracking (SpOT) facility consists of three 1-meter telescopes in the Santa Cruz Mountains of California. The telescope mounts are capable of slewing fast enough to rate-track Low Earth Orbit (LEO) satellites, and the optics have enough sensitivity to detect dim objects in Geosynchronous Earth Orbit (GEO).

During 2018, the SpOT facility has been operating predominantly as an autonomous Space Situational Awareness (SSA) system, making frequent observations of over 100 LEO satellites from the public Space Track catalog. This paper analyzes calibrated astrometry from these objects to characterize their onject classification using a simple Multiple Hypothesis Tracker.

**11:40 AAS 18-428** **Higher Order Polynomial Series Expansion for Uncertain Lambert Problem**

*Zachary Hall, Pennsylvania State University; Puneet Singla, Pennsylvania State University; Taewook Lee, University at Buffalo*

In this paper, the Uncertain Lambert Problem is solved using higher order polynomial series instead of the conventional first order one used in linear analysis. Coefficients of polynomial series are computed in a Jacobian free manner, providing a computationally tractable approach. This polynomial series is exploited to compute the density function for the Lambert solution given the probability density function for initial and final position vector. The method known as Conjugate Unscented Transformation (CUT) is used to construct coefficients of polynomial series by solving minimal Lambert problems through the intelligent sampling of the uncertain initial and final position vector space.

## Aug 21, 2018 Superior B – Proximity Missions & Formation Flying – I

## Tuesday Session 5 Proximity Missions, & Formation Flying-I

Chair: Andrew J. Sinclair, Air Force Research Laboratory
Co-Chair: Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)

**13:30 AAS 18-219** **Wheel Cluster Formation for HEO Satellites -- A Feasibility Study**

*Chia-Chun Chao, The Aerospace Corporation*

The concept of a wheel cluster formation in a single orbit plane has been demonstrated to be orbit dynamically stable, and cost effective in initial deployment and formation-keeping. This paper provides an in-depth feasibility study to further demonstrate, through numerical simulations, how the concept can be applied to highly elliptical orbit (HEO) satellites. In this study, a cluster of 10 closely sepa-rated sub-satellites is deployed and controlled at a Tundra orbit, a Molniya orbit and a geosynchronous transfer orbit (GTO). A proposed procedure of initial deployment from the center satellite is outlined. Results confirm long-term stability with minimal formation-keeping fuel cost.

**13:50 AAS 18-281** **Analytic Range-Only Initial Relative Orbit Determination Algorithm for Periodic Relative Motion**

*Baichun Gong, Nanjing University of Aeronautics and Astronautics; Shuang Li, Nanjing University of Aeronautics and Astronautics*

Range-only initial relative orbit determination (IROD) suffers from a well-known mirror solution problem in the context of linear dynamics during coasting flight. If the range-sensor offset from the spacecraft center-of-mass is considered, the relative orbit may be determined by using range-only measurements. This research developed an analytic solution to the range-only IROD problem for periodic relative motion by utilizing the range-sensor offset scheme integrated with attitude maneuver so as to exclude mirror solutions. The solution based on three different rotation schemes are analyzed and the feasible rotation scheme is obtained.  All these theoretical results are verified by a set of numerical simulation examples.

**14:10 AAS 18-284** **A Dynamically Distributed Control Architecture for Spacecraft Formation**

*Sumeet Gajanan Satpute, Luleå University of Technology; M. Reza Emami, Lulea Institute of Technology*

In this paper, a scalable formation control architecture based on Host-Avatar-Agent architecture is developed with dynamically distributed processing, capable of adjusting resources on-line in order to handle adding or removing spacecraft in the formation or in case of hardware failure. The architecture uses the inter-satellite communication framework for distributed processing that allows the computational load to be balanced among a dynamic set of three or more onboard processors. The proposed architecture can form the foundation for federated satellite systems. The performance of the proposed architecture is studied using a simulated formation scenario.

**14:30** **AAS 18-322** **Spacecraft Rendezvous in Cluttered Environments via Real-Time Optimal Trajectory Generation**

*Richard Linares, University of Minnesota; Brian Gaudet, The University of Arizona; Roberto Furfaro, The University of Arizona*

The primary contribution of this paper is a new approach to spacecraft rendezvous guidance that generates in real-time an optimal trajectory for autonomous rendezvous in space dynamical environments cluttered with cooperative and non-cooperative obstacles. The major innovation is a method for generating an initial solution to the optimal control problem that dramatically reduces computation time. We demonstrate the trajectory generation and tracking in a 3-DOF environment, with successful fuel-efficient rendezvous that avoid keep-out zones associated with the obstacles.

**14:50** **AAS 18-342** **A DOUBLE-LOOP OPTIMIZATION ALGORITHM FOR FUEL-OPTIMAL IMPULSIVE RENDEZVOUS UNDER A PATH CONSTRAINT**

*Youngkwang Kim, Yonsei University; Sang-Young Park, Yonsei University*

This paper addresses a fuel-optimal impulsive rendezvous problem under a path constraint. This study interprets the problem as a double-loop optimization problem. To address path constraints, a trajectory is divided into phases, and the outer problem is of finding optimal way-points minimizing constraint errors. The inner problem is of finding the optimal impulsive control for each phase. This study solves the inner problem using a duality-based optimization algorithm developed by the authors. To overcome non-differentiability, this study utilizes a pattern-search algorithm for solving the outer problem. As an example, an impulsive rendezvous trajectory near circular orbit with a visibility constraint is obtained.

**15:10** **Break**

**15:30** **AAS 18-384** **Incremental States for Precise On-Orbit Relative Knowledge in Formation Flight**

*Martin Cacan; Andrew Harris, NASA - JPL; Jack Aldrich, NASA - JPL; David Bayard, Jet Propulsion Laboratory; Carl Seubert, Jet Propulsion Laboratory*

High precision and close proximity formation flight is an enabling technology for future space missions and requires an on-board relative navigation capability that is accurate to the mm-level and robust to formation parameters. This work discusses an "incremental" formulation of the relative navigation problem which is invariant to formation size, robust to coupling between absolute and relative dynamics, and can undergo similarity transformations to smoothly incorporate either absolute or relative information without numerical issues.

**15:50** **AAS 18-390** **SAFE SPACECRAFT RENDEZVOUS WITH CONSTRAINED MODEL PREDICTIVE CONTROL**

*Ali Tevfik Büyükkoçak, Middle East Technical University; Ozan Tekinalp, METU Aerospace Engineering Dept.*

Rendezvous and docking problem of a pair of LEO spacecraft is addressed. Equations for the nonlinear orbital relative motion of spacecraft are derived and a simulation code for this motion is developed. For the control algorithm, linearized Hill-Clohessy-Wiltshire equations are used in chaser-target spacecraft configuration. Model Predictive Control (MPC) strategy is applied with safety constraints including debris avoidance and Line of Sight constraint. This includes the avoidance of a moving debris with an unbounded motion. A parametric study is also performed to obtain the proper prediction horizon and weighting matrices to be used in the simulations.

**16:30** **AAS 18-472** **Precision Control of Microsatellite Swarms Using Plasmonic Force Propulsion**

*Pavel Galchenko, Missouri University of Science & Technology; Henry J. Pernicka, Missouri University of Science & Technology*

Swarm formations used with scientific mission concepts require micronewton levels of thrust to enable precision formation flying and spacecraft pointing. Plasmonic force propulsion can provide needed levels of thrust to the microsatellite platform to enable these advanced missions. Three case studies are used to evaluate the performance of the swarm composed of microsatellites, each equipped with plasmonic thrusters. Control techniques are evaluated and adapted to provide robust and precise control under system disturbances, model uncertainties, and noise. Results show that relative position and pointing can be achieved to meet scientific objectives for a range of swarm precision formation missions.

**16:50** **AAS 18-478** **HALO ORBIT SPACECRAFT RENDEZVOUS WITH FINITE TIME CONVERGENE**

*Dandan Zheng; Jianjun Luo; Caisheng Wei, Northwestern Polytechnical University; RENYONG ZHANG, Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences*

The This paper considers the application of prescribed performance control （PPC） and disturbance observer (DO) to the Halo orbital autonomous spacecraft rendezvous problem subject to model uncertainties and external disturbances. With the aid of Lyapunov stability criteria, we first develop a new prescribed performance function (PPF), then , a continuous PPC-based PPF robust control law and its finite-time convergence characteristic is proven in theory. As the upper bound of the lumped uncertainty cannot be obtained in practice, a DO based composite DO-PPC controller is then presented to achieve high tracking accuracy even under actuator/ thruster failures and input saturations.

**17:10** **AAS 18-452** **Nonlinear Model for Relative Motion in Elliptical Orbit Based on Curvilinear Coordinate System**

*Huan Chen, School of Astronautics, Beihang University; Gustavo Alonso, Faculty of Aerospace Engineering, Technical University of Madrid; Xing Zhou, School of Astronautics, Beihang University; Yinrui Rao, China Academy of Engineering Physics; Chao Han, Beihang University; Xiaohui Wang, School of Astronautics, Beihang University; Javier Cubas, Faculty of Aerospace Engineering, Technical University of Madrid*

A nonlinear model for relative motion model in elliptical reference orbit is established based on the proposed curvilinear coordinate. The state transformation between the curvilinear coordinate and four kinds of ordinary orbit state parameters is derived. Then the relative state evolution with time is given out utilizing the trigonometric series expansion of mean anomaly. Because no approximation is introduced during the derivation, the accuracy of the transition is determined by the series expansion order. The proposed model is expected to be applied in long term and/or large scale of relative motion, such as the evolution of the space debris cloud.

**Aug 21, 2018 Superior A – Orbit Determination**

## Tuesday Session 6 Orbit Determination

Chair: Nagavenkat Adurthi, Texas A&M University
Co-Chair: Matthew Wilkins, Applied Defense Solutions

**13:30 AAS 18-202 GENERATING REALISTIC SENSOR OBSERVATIONS FOR OD ANALYSIS**

*David A. Vallado, Analytical Graphics, Inc.*

Satellite mission design requires simulating realistic observations to determine the expected accuracy of the orbit determination. Generating observations for satellites is complicated because actual observations are affected by many factors, including operational limitations. Target satellite catalogs must be accurate. Sensor access must be realistic and include additional constraints of scanning, range, lighting, frequency, elevation, cadence, observation scheduling, and sensor limitations. A generic architecture is developed to interact with a variety of simulation tools. Examples are provided using STK and ODTK for satellites observed from the AFSPC SSN, optical, transponder, and SLR networks.

**14:10 AAS 18-365 ORBIT ESTIMATION STRATEGY FOR LOW EARTH ORBIT AND GEOSTATIONARY SATELLITES**

*Abdulkadir Koker, Researcher at TUBITAK UZAY; Ozan Tekinalp, METU Aerospace Engineering Dept.*

In this paper, an orbit determination strategy that use batch filter and an unscented Kalman filter method is presented. For the orbit determination system, the range, azimuth, and elevation angles of the satellite measured from ground tracking stations are used for observations. An efficient filter initialization algorithm using the Gibbs method is proposed to provide an initial state. The batch filter is applied to improve initial conditions and to provide initial covariance. Finally, the unscented Kalman filter is used for state estimation. The effect of measurement noise and observation duration on orbit determination accuracy is also investigated, and presented.

**14:30** **AAS 18-386** **Sequential Orbit Estimation and Prediction Using Modified Equinoctial Elements**

*Waqar Zaidi, Applied Defense Solutions; Michael Mercurio, Applied Defense Solutions; Weston Faber, Applied Defense Solutions; Paul Schumacher, Air Force Research Laboratory*

The seminal Kalman Filter provides a sequential predict-then-update paradigm in which the first two moments of the posterior PDF are computed using new measurements. When expressed in Cartesian space, the orbital state uncertainty evolves in a non-Gaussian fashion. Modified Equinoctial Elements (MEE) describe a non-singular state space in which the uncertainty in the orbital state can be well-characterized by a Gaussian density function for extended periods of time. An end-to-end estimation framework is derived, whereby the recursive Bayesian prediction and update equations are expressed in MEE space. The results of the proposed approach are compared with a congruent application in Cartesian space.

**14:50** **AAS 18-391** **USING TRIANGULATION IN OPTICAL ORBIT DETERMINATION**

*Arun Bernard, Utah State University; Akhter Mahmud Nafi, Utah State University; David Geller, Utah State University*

The research presented in this paper focuses on orbit determination using simultaneous angle measurements from two separate observatories. These angle measurements are combined with the known observer locations to obtain a position vector of the satellite using basic trigonometry. This triangulation approach is investigated to determine its feasibility in initially determining the orbit of an object, and then refining the estimated orbit using the triangulated position vectors in a batch least squares estimation framework. The accuracy of this method with respect to different operating parameters such as timing errors, measurements errors, and baseline distance between observatories is investigated.

**15:10** **Break**

**15:50** **AAS 18-410** **Initial Orbit Determination with Velocity Vectors and Angles**

*Courtney Hollenberg, Rensselaer Polytechnic Institute; John Christian, Rensselaer Polytechnic Institute*

Classical methods of inital orbit determination (IOD) from Earth-bound observations are well established. Although traditional methods utilize range, position, and angle measurements, advancements in measurement techniques and sensor technologies have generated a need for new methods of IOD that utilize different parameters. Specifically, x-ray pulsar navigation (XNAV) allows for significantly more accurate measurements of an object’s velocity vector than its position which can be combined with line-of-sight unit vectors from sun sensors. A new method for initial orbit determination using only two velocity vectors and their respective lines-of-sight to the central body is presented. Theoretical results are validated through numerical simulations.

**16:10** **AAS 18-424** **Orbit Determination Using Vinti's Solution**

*Steven Wright, United States Air Force; William Wiesel, Air Force Institute of Technology*

Orbital altitudes congested with spacecraft and debris combined with recent collisions have all but negated the Big Sky Theory. As the sheer number of orbital objects to track grows unbounded so does interest in prediction methods that are rapid and minimally computational. Claimed as the "other solvable solution," the recently completed solution to orbital motion about the earth, based on Vinti's method and including the major effects of the equatorial bulge, opens up the prospect of much more accurate analytical models for space situational awareness. A preliminary examination of this solution is presented. A numerical state transition matrix is found

**16:30** **AAS 18-492** **Extended Kalman Filtering in Regularized Coordinates: Applications to Astrodynamics**

*Manoranjan Majji, Texas A&M University, College Station; Puneet Singla, Pennsylvania State University; David M. Ciliberto, Pennsylvania State University*

Peculiarities associated with the linear error theory and the Kalman filter implementations associated with a class of nonlinear transformations of mechanical systems of interest in astrodynamics are discussed in the paper. Change of the independent variable using a nonlinear implicit equation transforms the measurement equations appropriately and provides additional conditions associates with the measurement times that are perfectly known. Since regularization process introduces redundant coordinates, linear error theory to explicitly account for the state constraints is developed. The paper then studies the tradeoffs obtained by the linear error propagation in the time updates and the nonlinearity incurred in the measurement

**16:50** **AAS 18-366** **Defining and Propagating Uncertainty on Regularized Manifolds**

*Lorraine Weis, Applied Defense Solutions; Christopher Roscoe, Applied Defense Solutions; Michael Mercurio, Applied Defense Solutions; Paul Schumacher, Air Force Research Laboratory*

Converting orbital dynamics problems to regularized coordinate systems has a number of advantages. Historically, the main motivation for regularization was the significantly improved numerical accuracy given limited computation resources. With modern computation and numerical integration algorithms, a major benefit is the ability to analytically propagate uncertainty, and better understand the effects of perturbations on the character of uncertainty. By choosing a transform to a well behaved set of manifolds, we can extract meaningful metrics and quantify the behavior of density currents within the probability distribution.

### Aug 21, 2018 Maybird – Trajectory Design & Optimization – III

## Tuesday Session 7: Trajectory Design & Optimization-III

Chair: Roby Wilson, Jet Propulsion Laboratory
Co-Chair: Jeff Parker, Advanced Space

**13:30** **AAS 18-204** **Low-Thrust Transfer Nomograms**
*Salvatore Alfano, Center for Space Standards and Innovation*

A nomogram (or nomograph) is a graphical representation of three or more pieces of data; knowledge of two of those values visually leads to the other(s). Typically, a sharp pencil and keen eye will produce results within 5% of an exact numerical solution. Presented here is the construction of some useful nomograms regarding minimum-time, continuous low-thrust, circle-to-circle, orbit transfers in addition to nomograms relating miss distance to off-cycle thrust time as well as to maximum probability. The nomograms are useful for pre-mission planning and determining if further numerical processing is even worth the bother.

**13:50** **AAS 18-211** **NUMERICAL CHALLENGES IN CASSINI MANEUVER OPERATIONS**
*Mar Vaquero, Jet Propulsion Laboratory; Yungsun Hahn, Jet Propulsion Laboratory*

Launched in 1997 to observe Saturn and its system, Cassini successfully entered Saturn orbit in 2004 and impacted the planet on September 15, 2017 after 22 orbits each skimming over Saturn's cloud tops. The Cassini mission represents the most complex gravity-assist trajectory ever flown. As such, the Flight Path Control team encountered many difficulties along the way, resulting in a continuously evolving maneuver process. In this paper, we focus on the challenges presented by the well-known singularities in the transfer problem and the unexpected numerical instabilities in state propagations through flybys, maneuver algorithm convergence issues, and orbital element targeting difficulties.

**14:10** **AAS 18-462** **Elliptical Orbit Proximity Operations Differential Games**
*Eric Prince, Air Force Institute of Technology; Joshuah Hess, Air Force Institute of Technology; Ryan Carr, Air Force Research Laboratory; Richard Cobb, Air Force Institute of Technology*

Differential games are formulated and solved for an inspector satellite operating nearby a resident space object (RSO) in an elliptical orbit, where both players use a constant, steerable thruster. For each differential game, the goal of the inspector satellite is to minimize the time to achieve an inspection goal, while the goal of the RSO is to delay that condition as long as possible. The following inspection goals are examined: a) intercept; b) rendezvous; c) obtain Sun vector; d) match energy; e) obtain Sun vector and match energy; and f) match energy and remain close throughout the ensuing orbit.

**14:30** **AAS 18-293** **Trajectory Design for the Korea Pathfinder Lunar Orbiter(KPLO)**
*Su-JIN Choi, Korea Aerospace Research Institute; Ryan Whitley, NASA; Gerald Condon, NASA; Michel Loucks, Space Exploration Engineering (SEE); Jae-ik Park, Korea Aerospace Research Institute; Seok-Weon Choi, Korea Aerospace*

*Research Institute; Se-Jin Kwon, Korea Advanced Institute of Science and Technology*

The Korea Pathfinder Lunar Orbiter(KPLO) is a one-year duration mission to be flown in a 100 km lunar polar otbit. The spacecraft is a three-axis stabilized attitude control with six instruments. KPLO will use a 3.5 phasing loop transfer trajectoy to the Moon. This trajectory design features a high first apogee altitude(>300,000km) that provides a long duration check-out time and receives lunar gravity perturbations that raise the second perigee with maneuvers. To choose critical parameters that minimize Delta-V, several trade-off studies on several trajectory options are performed. These parameters are studied over a month-long launch period in December 2020.

**14:50** **AAS 18-436** **Transfer from TLI to Lunar Polar Orbit via Ballistic Lunar Capture**

*Anthony Genova, NASA; Brian Kaplinger, Florida Institute of Technology*

The presented trajectory design connects a trans-lunar injection (TLI) trajectory to lunar polar orbit via ballistic lunar capture. The TLI is assumed to originate from NASA Kennedy Space Center with solutions presented for a full 360 degree sweep of the TLI's node. The design is compatible with small spacecraft equipped with propulsion systems that lack sufficient thrust to enter lunar orbit from a traditional lunar orbit transfer such as the LunaH-Map cubesat (~1 mN thrust capability) which is planning to share a ride to a TLI trajectory with EM-1 on SLS.

**15:10** **Break**

**15:30** **AAS 18-325** **Trajectory Design for LEO to lunar halo orbits using a hybrid optimization method**

*Davide Conte, Pennsylvania State University; Guanwei He, Pennsylvania State University; David B. Spencer, Pennsylvania State University; Robert G. Melton, Pennsylvania State University*

In this paper a simple and efficient way of computing impulsive maneuver transfers from a user-defined Low Earth Orbit (LEO) to a desired lunar halo orbit around the Earth-Moon Lagrange point 2 (EML2) utilizing a heuristic optimization method is presented. Fireworks, a hybrid heuristic optimization method, is utilized in order to obtain solutions with acceptable fidelity. The dynamical framework utilized is the Circular Restricted Three-Body Problem (CR3BP). Sample LEO to lunar halo trajectories along with their required delta-v costs and Time-of-Flight (TOF) are provided and compared to known numerical techniques to assert the validity of the proposed method.

**15:50** **AAS 18-397** **Optimal Low-Thrust Trajectory Correction with Neural Networks**

*Nathan Parrish, University of Colorado at Boulder; Daniel Scheeres, University of Colorado at Boulder*

Although electric propulsion technologies give spacecraft a leap forward in maneuverability over time relative to chemical propulsion, the greater lifetime delta-v comes at the expense of thrust. The traditional paradigm of large, impulsive maneuvers with later clean-up is not relevant to low-thrust trajectories. In highly sensitive dynamical environments such as the Earth-Moon system, frequent ground contacts are required to maintain low-thrust spacecraft in a tight control box. Here we introduce neural networks as a way to map position and velocity error to an updated low-thrust optimal control policy. Promising results are shown for interplanetary and CRTBP force models.

**16:10** **AAS 18-399** **A Unified Approach to Optimization of Low-Thrust and Impulsive Orbit Maneuvers**

*Ehsan Taheri, Texas A&M University; John L. Junkins, Texas A&M University*

This paper builds upon a recently introduced concept of switching surface (SS) and performs an in-depth analysis of a SS for an interplanetary mission from the Earth to the Mars. Indirect method of optimal control theory along with Lawden's primer vector theory provide a unified systematic means to study continuous low-thrust and impulsive trajectories. The concept of early-arrival boundary, which has its own profile is explained. A bifurcation is encountered in the generated SS, which in general, triggers the creation of thrust arcs. The topology of SS provides new tools for mission designers and enables insights to perform useful trade-off for sizing vehicles.

**16:30** **AAS 18-411** **Interplanetary Trajectory Design Using a Recurrent Neural Network and Genetic Algorithm**

*Paul Witsberger, Purdue University; James Longuski, Purdue University*

A low-thrust gravity-assist trajectory design tool is proposed that uses a recurrent neural network to create a spacecraft steering strategy. The recurrent neural network is trained using a combination of dynamic backpropagation and evolutionary strategies. A recurrent neural network is expected to be more robust than a feedforward neural network due to its ability to represent dynamical systems and to have a "memory" of past events. Dynamic backpropagation is proposed as a training method in order to generate an intelligent starting guess that may shorten the amount of time spent in the genetic algorithm.

**16:50** **AAS 18-296** **STATISTICAL APPROACHES TO INCREASE EFFICIENCY OF LARGE-SCALE MONTE-CARLO SIMULATIONS**

*David Shteinman, Industrial Sciences Group ; Thibaud Teil, University of Colorado, Boulder ; Scott Dorrington, Industrial Sciences Group ; Jaslene Lin, Industrial Sciences Group ; Hanspeter Schaub, University of Colorado; John P. Carrico, Space Exploration Engineering, Inc.; Lisa Policastri, Space Exploration Engineering (SEE)*

Many numerical astrodynamics analyses are characterized by a large input space with dispersions on the inputs. Furthermore, the underlying input-output relationships are nonlinear. Monte Carlo simulations are used but with long and expensive run times. We adapt a method for astrodynamics simulations from industrial statistics to 1) Significantly reduce the run time of large Monte Carlo simulations; 2) Ensure the simulation covers a wider range of worst case scenarios for significantly less runs 3) Increase the efficiency of Sensitivity Analysis and Optimization by using a fast/computationally cheap approximate model. We illustrate the method in case studies on attitude control and trajectory design.

**17:10** **AAS 18-442** **Robust Trajectory Optimization for Mars Atmospheric Entry Based on Uncertainty Propagation**

*Xiuqiang Jiang, Nanjing University of Aeronautics and Astronautics; Shuang Li, Nanjing University of Aeronautics and Astronautics*

A robust optimization procedure for Mars atmospheric entry trajectory under uncertainty is newly developed in this paper. Uncertainty propagation due to both initial state and dynamical parameters are taken into account. The uncertainty propagation is combined into the robust optimization problem which is then transformed into an equivalent deterministic one in the expanded higher-dimensional state space by polynomial chaos expansion, and it is solved by hp-adaptive pseudospectral method. The obtained optimal trajectory is more reliable and robust to uncertainties compared to traditional deterministic and reliability-based optimization.

**Aug 21, 2018 Cirque – Spacecraft GNC – III**

## Tuesday Session 8 Spacecraft GNC-II

Chair: Diane Davis, a.i. solutions, Inc.
Co-Chair: Marcus Holzinger, University of Colorado Boulder

**13:30** **AAS 18-485** **Computational Guidance for Mars Entry and Powered Descent**

*Xiuqiang Jiang, Nanjing University of Aeronautics and Astronautics; Roberto Furfaro, The University of Arizona; Shuang Li, Nanjing University of Aeronautics and Astronautics*

A rigid mid lift-to-drag ratio vehicle concept is newly put forward by NASA in 2017 as the prefer one for future human Mars landing mission. Traditional low-lift Mars EDL is replaced by mid-lift high-mass atmospheric entry and powered descent. Integrated guidance is desired to achieve the least propellant usage and pin-point landing. The aim of this paper is to propose a solution of the integrated guidance for mid-lift high-mass Mars entry and powered descent, using collaborative optimization strategy. It is a computational guidance without the need for off-line trajectory planning and real-time tracking.

**13:50** **AAS 18-229** **Centroiding and Sizing Optimization of Ellipsoid Image Processing Using Nonlinear-Least Squares**

*Stoian Borissov, Texas A&M University; Daniele Mortari, Texas A&M University*

This paper covers the development and application of image processing algorithms developed by Texas A&M for NASA Johnson Space Center, that are used on images of celestial target bodies when performing optical navigation (OpNav).The algorithms work by first creating an initial estimate of the apparent size and centroid of the observed body is produced. This initial estimate is refined through a nonlinear least squares process. The focus of this paper will be to provide the mathematical development of the nonlinear least squares and also demonstrate its implementation in the Orion OpNav system.

**14:10** **AAS 18-258** **A New Approach to Reliable Powered Descent Guidance Problem using Convex Optimization**

*Kazuya Echigo, The University of Tokyo; Takashi Kubota, Institute of Space and Astronautical Science, JAXA*

Planetary landing missions have received a lot of attention all over the world. In order to increase the success rate of the mission, the spacecraft should land on the target body safely without receiving any command from the ground station. To meet this demand, it is necessary to descend as vertically as possible to the target point autonomously and maintain the field of view while landing. In this paper, a new convex optimization based approach is proposed to solve the maximum-safety powered-descent guidance problem. The validity of the proposed method is shown by numerical simulations.

**14:50** **AAS 18-270** **Closed Loop Guidance Trade Study for Space Launch System Block-1B Vehicle**

*Naeem Ahmad, NASA; Matthew Hawkins, Jacobs Space Exploration Group; Robin Pinson, NASA; Gregory Dukeman, NASA; Paul Von der Proten, NASA; Thomas Fill, C.S. Draper Laboratory*

The Space Launch System (SLS) Block-1B vehicle includes a low thrust-to-weight upper stage, which presents challenges to the ascent guidance algorithm. A trade study was conducted to evaluate two alternative guidance algorithms: 1) Powered Explicit Guidance (PEG), based on the implementation of PEG for the Block-1 vehicle, and 2) OPGUID, an algorithm developed at Marshall Space Flight Center (MSFC) and used on Constellation and other GN&C projects. The design criteria, approach, and results of the trade study are given, as well as other impacts and considerations for Block-1B type missions.

**15:10** **Break**

**15:30** **AAS 18-287** **AN OPTIMAL CAPTURE BRAKING METHOD FOR LUNAR SOFT LANDING**

*Chengchao Bai; Jifeng Guo*

Any braking deviation can cause the deviation of the orbit, which will lead to the failure to capture or impact the lunar surface ahead of time. In order to make the lunar module effectively captured, the paper proposes a method to capture braking based on PSO (particle swarm optimization), the constraints of the method are the final lunar orbit eccentricity and the final lunar orbit near point height. The results show that under the framework of PSO algorithm, using the fixed thrust direction braking strategy to capture braking can satisfy all the constraints well and can optimize the fuel consumption.

**15:50 AAS 18-308 Closed-form Optimal Impulsive Control of Spacecraft Formations Using Reachable Set Theory**

*Michelle Chernick, Stanford University; Simone Damico, Stanford University*

This paper addresses the spacecraft relative orbit reconfiguration problem of minimizing the delta-v cost of a set of impulsive control actions while achieving a desired state in fixed-time. The problem is cast into relative orbit element space, which allows for the straightforward inclusion of perturbations in linear time-variant form. Reachable set theory is used to formulate a novel metric, the reachable delta-v minimum, for assessing the optimality of a maneuver scheme. For the first time in literature, closed-form maneuver schemes are derived in orbits of arbitrary eccentricity and shown to be globally energy-optimal. The proposed algorithms are validated in high-fidelity

**16:10 AAS 18-363 Deep Learning for Autonomous Lunar Landing**

*Roberto Furfaro, The University of Arizona; Ilaria Bloise, Politecnico di Milano; Marcello Orlandelli, Politecnico di Milano; Richard Linares, University of Minnesota; Francesco Topputo, Politecnico di Milano; Pierluigi Di Lizia, Politecnico di Milano*

In this paper we design, test and evalaute a set of deep neural networks, i.e. Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN) capable of predicting fuel-optimal control actions to perform autonomous Moon landing, using only raw images taken by on board optical cameras.

**16:30 AAS 18-201 Time-optimal Spacecraft Reorientation with Attitude Constraints Based on A Two-stage Strategy**

*Juntang Yang, Institute of Space Systems at TU Braunschweig; Enrico Stoll, Institute of Space Systems at TU Braunschweig*

It is difficult to solve a time-optimal reorientation problem in the presence of complex attitude constraints even with direct methods. This paper proposes a new method to accelerate the computation based on a two-stage strategy. Firstly a feasible solution of the constrained reorientaiton maneuver is obtained using Bezier quaternion curves and the inverse dynamics. Then the feasible solution obtained is used as an initial guess for the pseudospectral optimizer. Compared with the pseudospectral method alone, the proposed two-stage strategy can reduce the computation time to various extent. In some cases, the proposed method can be four times faster than the pseudospectral method alone.

**16:50 AAS 18-371 Information-theoretic Sensor Scheduling under Communication Constraints**

*Kirsten Tuggle, The University of Texas at Austin; Maruthi R. Akella, University of Texas at Austin*

The subject of estimation and control subject to information constraints has been of interest to the aerospace community since the 1960s. This paper focuses on the fundamental question of sensor scheduling in the Linear-Quadratic-Gaussian (LQG) framework. A main contribution is the use of information-theoretic tools in posing, resolving, and interpreting the problem. In doing so, certain new insights on properties of the flow of information within the Kalman filter (KF) will be provided.

**17:10** **AAS 18-300** **An Adaptive Non-singular Terminal Sliding Mode Tracking Control Using Neural Networks for Space Manipulators Actuated by CMGs**

*Xinhui Xia, School of Astronautics, Beihang University; Yinghong Jia; Shijie Xu; Xinlong Wang, Beihang University*

An adaptive non-singular terminal sliding mode trajectory tracking control scheme based on neural networks is proposed for rigid space manipulators with control moment gyroscopes (CMGs) as reactionless actuators. A key feature of this scheme is that an adaptive neural network is used to learn the upper bound of the system lumped uncertainties with no prior knowledge. The other feature is that a non-singular terminal sliding surface is constructed to ensure that the tracking error converges to zero in finite time for the closed loop system which is uniformly ultimately bounded. Numerical results verify the effectiveness of the proposed controller

# Wednesday August 22, 2018

**Aug 22, 2018 Superior A – Astrodynamics – III**

**Wednesday Session 1 Astrodynamics-III**

Chair: Rohan Sood, University of Alabama
Co-Chair: Nagavenkat Adurthi, Texas A&M University

**8:00** **AAS 18-350** **DYNAMICAL EFFECTS OF SOLAR RADIATION PRESSURE ON THE DEFLECTION OF NEAR-EARTH ASTEROIDS**

*Luis Marchi, National Institute for Space Research; Flaviane Venditti, Arecibo Observatory; Diogo Sanchez, National Institute for Space Research - INPE; Antonio Fernando Bertachini Prado, INPE*

The paper presents a mathematical model for the dynamics of an asteroid attached by a long tether to an inflatable balloon. The model is then used to study the effect that the tether length and the solar radiation pressure (acting on the balloon surface) exert on the deflection of a larger Potentially Hazardous Asteroid (PHA). As a starting point, the tether is inextensible and massless and the motion is described only in the plane of the orbit of the PHA around the Sun.

**8:20** **AAS 18-361** **Planar orbit and attitude dynamics of an Earth-orbiting Solar Sail under J2 and atmospheric drag effects**

*Narcis Miguel Banos, Politecnico di Milano; Camilla Colombo, Politecnico di Milano*

In this paper we study planar orbit+attitude dynamics of an uncontrolled spacecraft, building on known de-orbiting strategies. The dynamics are studied in mean Keplerian elements and restricted to rotations around one of the principal axes of the spacecraft. We consider spacecrafts with a solar sail with either flat or trapezoidal shape, and we investigate stable or slowly-varying attitudes affected by disturbances due to the $J_2$ effect, Solar Radiation Pressure, and atmospheric drag, with special emphasis on orbits where two of these effects are of the same order of magnitude. A sensitivity analysis of the aperture of the sail is performed.

**8:40 AAS 18-369 DYNAMICS OF ASYMMETRICAL MOTORIZED MOMENTUM EXCHANGE TETHER BY KEPLER-QUATERNION METHOD**

*Yong YANG, China Academy of Engineering Physics*

Using the momentum exchange principle, the error dynamics model of the motorized momentum exchange tether (MMET) is assessed by considering structural deviation. The effects of deviations and differences in tethers' lengths and in payloads' masses are investigated. A new Kepler-Quaternion method is studied to build the orbital error dynamic equations and attitude kinematic equations. The numerical simulation results show that the difference in tethers' length and difference in payloads' mass have similar impacts on the chief satellite's orbit of the MMET. Specifically, the tension due to structure bias and tether rotation increasingly affect the chief satellite's orbit

**9:00 AAS 18-274 IBEX Revisited: Operational Results for Long-Term Cislunar Orbit Propagation**

*John P. Carrico, Space Exploration Engineering, Inc.; Lisa Policastri, Space Exploration Engineering (SEE); Stephen Lutz*

In June 2011, the Interstellar Boundary Explorer (IBEX) spacecraft performed maneuvers transferring from its original science orbit to a 3:1 lunar resonant orbit for its extended mission. Prior to the transfer, the IBEX Flight Dynamics Group (FDG) performed analyses to select precise resonant orbit to meet perigee altitude and eclipse duration requirements. Since then, IBEX has been performing its mission without any need for orbit corrections. The FDG continues to monitor the orbit, comparing the actual orbit and eclipse data with the predictions. In this paper we compare the predictions with the actual values and show the prediction evolution.

**9:20 AAS 18-321 Method of Characteristics based Nonlinear Filter: With Application to Space Object Tracking**

*Nagavenkat Adurthi, Texas A&M University; Manoranjan Majji, Texas A&M University, College Station*

This paper deals with the development of a nonlinear filter based on the method of characteristics. For the special case where there is no process noise, the evolution of the probability density function is governed by the stochastic Liouville equation which is a quasi-linear partial differential equation. We leverage the method of characteristics and the Bayes' rule to efficiently and exactly propagate the conditional probability along trajectories. The filter estimates are then computed at every time step using the trajectories and their corresponding probabilities. We illustrate the efficacy of our approach using the Two-Body problem dynamics.

**9:40 Break**

**10:20 AAS 18-435 A HIGH ORDER FILTER FOR ESTIMATION OF NONLINEAR DYNAMIC SYSTEMS**

*Taewook Lee, University at Buffalo; Puneet Singla, Pennsylvania State University; Manoranjan Majji, Texas A&M University, College Station*

In this paper, a high order filter is presented for estimation of nonlinear dynamic systems. The proposed filter computes higher order moment update equations in a Jacobian free manner and a computationally attractive manner. Compared to the conventional filters such as the Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF), the proposed filter captures desired order of statistical moments by making use of the higher order state transition matrices developed in our previous works, providing more accurate estimates through sparse measurements.

**10:40 AAS 18-408 Transiting Exoplanet Survey Satellite (TESS) Flight Dynamics Commissioning Results and Experiences**

*Joel Parker, NASA Goddard Space Flight Center; Ryan Lebois, Applied Defense Solutions, Inc.; Stephen Lutz; Craig Nickel, Applied Defense Solutions; Kevin Ferrant, University of Colorado at Boulder; Adam Michaels, Omitron*

The Transiting Exoplanet Survey Satellite (TESS) will perform the first-ever spaceborne all-sky exoplanet transit survey and is the first primary-mission application of a lunar-resonant orbit. Launched on April 18, 2018, TESS completed a two-month commissioning phase consisting of three phasing loops followed by a lunar flyby and a final maneuver to achieve resonance. During the science orbit, no further station-keeping maneuvers are planned or required. NASA Goddard Space Flight Center is performing flight dynamics operations for the mission. This paper covers the design, implementation, and results from TESS commissioning, including the projected performance of the final science orbit.

**11:00 AAS 18-373 Design of a Flexible, Scalable, and Extensible Cloud-Based Multi-Mission Flight Dynamics System**

*Russell DeHart, KBRwyle; Rebecca Besser, KBRwyle; Haisam Ido, KBRwyle; Ryan Jim, KBRwyle; Joseph Kaminsky, KBRwyle; Craig E. Roberts, KBRwyle; Jennifer Sager, KBRwyle; Noah Williams, KBRwyle; John Zarek, KBRwyle; Eduardo Valente, Emergent Space Technologies; Dale Fink, NASA Goddard Space Flight Center*

In October 2017, navigation operations for the ACE and Wind spacecraft operated by the Space Science Mission Operations Project at the NASA Goddard Space Flight Center transitioned to the Navigation as a Service (NaaS) flight dynamics system. NaaS uses the Amazon Web Services GovCloud and the virtual multi-mission environment as the high-reliability, cost-effective core architecture. The NaaS design produces a repeatable and reusable process which lowers overhead to analysts by automating the collection of elements necessary to create workspaces, perform execution of the flight dynamics engine, and deliver products to customers, and allowing operator-in-the-loop troubleshooting of flight dynamics analysis.

**11:40** **AAS 18-455** **RELATIVE EQUATIONS OF MOTION USING A NEW SET OF ORBITAL ELEMENTS**

*Pardhasai Chadalavada, Wichita State University; Atri Dutta, Wichita State University*

In this paper, we consider the relative equations of spacecraft motion in terms of a new set of orbital elements that includes the components of the angular momentum in the inertial reference frame, the components of the eccentricity vector in a non-inertial reference frame that is obtained following a 2-1-3 rotation sequence, and a true-anomaly-like angle. We provide a detailed formulation of the relative dynamics using orbital element differences in the proposed state parameters. Using numerical simulations, we compare the formulation with Hill-Clohessy-Wiltshire equations of relative motion.

### Aug 22, 2018 Cirque – Asteroid and Non Earth Orbiting Missions – II

## Wednesday Session 2 Asteroid and Non Earth Orbiting Missions-II

Chair: Simone Damico, Stanford University
Co-Chair: Mar Vaquero, Jet Propulsion Laboratory

**8:00** **AAS 18-238** **A Consistent Small Body Navigation Filter Using Flash-Lidar Data and Bezier Triangles**

*Benjamin Bercovici, University of Colorado Boulder, Colorado Center for Astrodynamics Research (CCAR); Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)*

We propose an algorithm relying on Flash-Lidar data to reconstruct the shape model of an orbited object, train an uncertainty model representative of shape reconstruction imprecision and sensor noise using a maximum-likelihood approach combined with a Particle-In-Swarm Optimizer, and perform model-based relative navigation by comparing range measurements from the on-board shape model to those provided by a Flash-Lidar sensor. Our algorithm yielded a satisfying estimate of the shape model of interest, along with a consistent measure of the range error that was derived by means of likelihood maximization over the measured range residuals.

**8:20** **AAS 18-280** **A single crater based optical navigation method for autonomous asteroid landing**

*Meng Yu, Nanjing University of Aeronautics and Astronautics*

This paper proposes a novel terrain relative navigation (TRN) method for autonomous asteroid landing. The proposed method is designed to use only one crater as the visual landmark. An efficient method is first developed to extract the shadow to contour ratio (SCR) from the 3D crater model by assuming the a-priori knowledge of the solar direction during descent. The crater matching is then achieved by comparing the SCR of detected crater in descent images and that of 3D crater model. Simulation results demonstrate that the proposed algorithm can achieve a relatively high-precision autonomous pin-point asteroid landing, even under a poor landmark detection scenario.

**8:40** **AAS 18-299** **Hybrid Gravity Models for Itokawa, Kleopatra, and Comet 67P/C-G**

*Patrick Wittick, The University of Texas at Austin; Ryan Russell, The University of Texas at Austin*

Future small body missions will demand tools that accelerate the mission design process. Here, a recently introduced hybrid gravity model is applied to several small bodies of interest. The gravity model fits superposed point-mascon and spherical harmonic fields to a high-fidelity polyhedral model, resulting in reasonably fast and globally valid models. Many diverse models for each body are evaluated and optimized, minimizing runtime, field errors and memory footprints. Several Pareto-optimal models for each body are examined in detail and archived. Results indicate the performance of such models exceeds that of lower-resolution polyhedral models and is similar to high-resolution spherical harmonics.

**9:20** **AAS 18-491** **Europa Lander Trajectory Design Using Lissajous Staging Orbits**

*Ricardo Restrepo, University of Texas at Austin; Ryan Russell, The University of Texas at Austin; Martin Wen-Yu Lo, Jet Propulsion Laboratory*

Lissajous orbits and their approximate invariant manifolds are used to generate landing trajectories at Europa. Each Lissajous is discretized into individual revolutions that approximate a periodic orbit. The approximate invariant manifolds of the combined individual revolutions  generate more surface coverage than those of simple libration point orbits. The approximate stable manifolds propagated backwards in time can provide direct connection to the last phase of a moon tour. The strategy developed produces ballistic landing trajectories with a wide surface coverage, and allows for the decoupling of the landing and moon tour phase by using the Lissajous as an intermediate staging orbit.

**9:40** **Break**

**10:00** **AAS 18-402** **Dynamics Analysis of Hopping Rovers on irregularly-shaped Small Bodies**

*Xiangyu Li, Beijing Institute of Technology; Syracuse Univercity; Amit Sanyal, Syracuse University; Rakesh Warier, Syracuse University; Qiao Dong, Beijing Institute of Technology*

In this paper, the 3-D dynamics model of a hopping rover on an irregular-shaped small body is established based on a polyhedron model. The hopper is modeled as a cube with only three reaction wheel actuators. Initialization of a hop and determination of sliding behavior on the surface are analyzed. Then the orbital-attitude couple motion after hopping is calculated. Based on a model for the asteroid Bennu, the influence of surface coefficients, friction factors and other factors on hopping motions are discussed. Finally, the possibility of lift off from the surface of small bodies by hopping is studied.

**10:20** **AAS 18-416** **{Preliminary Interplanetary Mission Design and Navigation for the Dragonfly New Frontiers Mission Concept**

*Christopher Scott, The Johns Hopkins University Applied Physics*

*Laboratory; Martin Ozimek, The Johns Hopkins University Applied Physics Laboratory; Douglas Adams, The Johns Hopkins University Applied Physics Laboratory; Ralph Lorenz, The Johns Hopkins University Applied Physics Laboratory; Shyam Bhaskaran, Jet Propulsion Laboratory; Rodica Ionasescu, Jet Propulsion Laboratory; Mark Jesick, Jet Propulsion Laboratory; Frank Laipert, Jet Propulsion Laboratory*

Dragonfly is one of two mission concepts selected in December 2017 to advance into Phase A of NASA's New Frontiers competition. Dragonfly would address the Ocean Worlds mission theme by investigating Titan's habitability and prebiotic chemistry and searching for evidence of chemical biosignatures of past (or extant) life. A rotorcraft lander, Dragonfly will capitalize on Titan's dense atmosphere to enable mobility and sample materials from a variety of geologic settings. This paper describes Dragonfly's mission design giving a complete picture of the inherent tradespace and outlines the design process from launch to atmospheric entry.

**10:40 AAS 18-217 Coverage Analysis for Positioning in the Asteroid Main Belt using a Space Navigation Infrastructure**

*Luisa Buinhas, Institute of Space Technology & Space Applications; Alena Probst, Bundeswehr University Munich; Roger Foerstner, University of the German Armed Forces Munich*

The paper proposes a navigation and communications infrastructure which supports Main Asteroid Belt exploration activities. In order to identify coverage conditions, different locations in space for this infrastructure are analysed with respect to triangulation-based positioning accuracy. The locations considered are the libration points of the Sun-Mars and Sun-Jupiter systems. Results show that the L3, L4 and L5 libration points of the Sun-Jupiter system provide the required accuracy the highest percentage of time, but combinations between these three libration points and the L4 and L5 points of the Sun-Mars system removes accuracy gaps in the coverage analysis.

**11:00 AAS 18-241 Mission Design for the Exploration of Ice Giants, Kuiper Belt Objects and Their Moons using Kilopower Electric Propulsion**

*Steven McCarty, NASA Glenn Research Center; Steven Oleson, NASA Glenn Research Center; Lee Mason, NASA Glenn Research Center; Marc Gibson, NASA Glenn Research Center*

NASA is currently developing a scalable 1-10-kW class fission reactor, known as Kilopower. A Kilopower Electric Propulsion (KEP) system could uniquely provide considerable propulsive capability in a class between REP and high-power NEP systems.This paper describes the KEP mission design analyses completed to explore possible orbiting missions to the outer solar system with Uranus, Neptune, and Pluto as destinations. These analyses include a broad search of interplanetary trajectories utilizing multiple gravity assists to identify a range of mission opportunities and design of potential orbit insertions trajectories around the destinations that may be uniquely enabled by KEP.

**11:20** **AAS 18-283** **Applications of the Dynamic N-Dimensional K-Vector**

*Carl Leake, Texas A&M University; Javier Roa, NASA / Caltech JPL; Daniele Mortari, Texas A&M University*

Selecting a mission to a celestial body can require searching through a database of missions to various celestial bodies that has missions which are added and removed over time. Searching through such a database requires an algorithm that can search in massive, multi-dimensional databases and be updated when the database changes. This paper presents a technique, called the dynamic n-dimensional k-vector that can do just that. The dynamic n-dimensional k-vector extends the n-dimensional k-vector to dynamic databases by providing a way to update the four constituents of the n-dimensional k-vector when elements are added or removed from the corresponding database.

**11:40** **AAS 18-248** **Analysis of the 3GM Gravity Experiment of JUICE**

*Paolo Cappuccio, Sapienza University of Rome; Mauro Di Benedetto, Sapienza Università di Roma; Gael Cascioli, Sapienza University of Rome; Luciano Iess, Sapienza University of Rome*

The ESA's JUICE mission will provide a thorough investigation of the Jupiter system and the Galilean moons through a suite of ten different scientific instruments. JUICE will perform flybys of Europa and Callisto, and will orbit about Ganymede in the last phase of the mission. The 3GM experiment will exploit accurate Doppler and range measurements to determine the moons' orbits and gravity fields (both static and tidal) and infer their interior structure. This paper presents the attainable 3GM gravity experiment performances. Our analysis includes the use of a high-accuracy accelerometer to remove the dynamical noise induced by propellant sloshing.

**Aug 22, 2018 Maybird – Trajectory Design & Optimization – IV**

## Wednesday Session 3 Trajectory Design & Optimization-IV

Chair: Tarek Elgohary, University of Central Florida

**8:00** **AAS 18-489** **An analytical 3D shape-based algorithm based on orbits interpolation for multi-revolutions low-thrust trajectory optimization with eclipses and perturbations**

*Jacopo Prinetto, Politecnico di Milano ; Michèle Lavagna, Politecnico di Milano*

A novel approach is proposed to extend to the 3-dimensional domain the well-known shape based trajectory design for low thrust profiles generation . The method outputs a trajectory closer to the physical solution.  The algorithm succeeds in designing trajectories with thousands of revolutions, such as in planetocentric scenarios. Practical mission constraints are easily formalized, such as maximum thrust  threshold and eclipses; moreover, relevant perturbations effects can be considered; free and fixed time of flight are manageable as well.  The approach is fully analytic, beneficial to significantly lower the computational load, well suited for complex mission scenarios optimal solutions fast detection.

**8:20** **AAS 18-264** **Exploration of three-dimensional orbit bifurcations in the CRTBP using cell mapping**

*Dayung Koh, Jet Propulsion Laboratory; Rodney L. Anderson, Jet Propulsion Laboratory/Caltech*

The natural dynamical behavior and periodic solutions around Europa have been studied using cell mapping.
This study is especially focused on spatial periodic orbits and bifurcation phenomena. The proposed method is generic for various classes of problems including non-autonomous systems and unknown types of periodic solutions. It also provides a way to compute bifurcation diagrams that connect the different orbit types and produce a framework from which to obtain a more complete understanding of the orbit family options in this system. The result contains several periodic orbit families around Europa and bifurcation studies.

**8:40** **AAS 18-398** **Low-Thrust GTO-to-GEO Trajectory Optimization and Tracking**

*Uros Kalabic, Mitsubishi Electric Research Laboratories (MERL); Avishai Weiss, MERL; piyush grover, MERL*

In this work, we consider the problem of low-thrust GTO-to-GEO osculating trajectory optimization and tracking. We exploit analytical solutions available in the averaged planar problem and use homotopy methods to obtain fuel- and time-optimal osculating trajectories using direct numerical optimal control tool GPOPS-II. We employ an attitude controller for tracking the thrust vector profile obtained from the optimal trajectories, while maintaining desired solar panel alignment. We simulate the operation of our controller numerically using MATLAB and the high-fidelity Systems Tool Kit (STK) software, and show excellent tracking performance of the controller.

**9:00** **AAS 18-401** **A Novel Multi-Spacecraft Interplanetary Global Trajectory Optimization Transcription**

*Sean Napier, University of Colorado Boulder; Jay McMahon, CCAR (Colorado Center for Astrodynamics Research)*

As the frontier of space exploration continues to advance, so does the design complexity of future interplanetary missions. This includes "Distributed Spacecraft Missions;" where multiple spacecraft coordinate to perform shared objectives. Current approaches for the global optimization of these Multi-Vehicle Missions (MVM) are prone to a variety of shortcomings including laborious iterative design, considerable human-in-the-loop effort, breakdown of the global multi-vehicle problem into several separate trajectory optimization subproblems (resulting in suboptimal solutions where the whole is less than the sum of its parts). We present an innovative fully-automated technique which frames interplanetary MVMs as multi-agent, multi-objective hybrid optimal control problems.

**9:20** **AAS 18-423** **Mars Ion and Sputtering Escape Network (MISEN) Mission Concept**

*Jeff Parker, CCAR/Advanced Space, LLC; Nathan Parrish, University of Colorado at Boulder; Robert Lillis, UC Berkeley; Shannon Curry, UC Berkeley; David Curtis, UC Berkeley; Janet Luhmann, UC Berkeley; Jordi Puig-Suari,*

*Tyvak; Christopher Russell, UCLA Dept. of Earth and Space Sciences; David Brain, CU Boulder LASP*

The Mars Ion and Sputtering Escape Network (MISEN) is a mission concept developed through the Planetary Science Deep Space SmallSat (PSDS3) program supported by NASA's Science Mission Directorate. MISEN includes three small satellites deployed as secondary payloads aboard a primary mission destined for Mars, the Moon, or another orbit of similar launch energy. The three satellites each use solar electric propulsion to transfer to Mars, rendezvous with Mars, and descend to three different orbits. Once there they conduct an investigation characterizing ion and sputtering escape mechanisms in the Martian atmosphere. This paper describes the mission challenges and solutions.

**9:40 Break**

**10:00 AAS 18-431 Analytic Expressions for Derivatives from Series Solutions to the Three Body Problem**

*Nathan Strange, NASA / JPL*

This paper presents a notation system to facilitate to solution of differential equations via Taylor series expansions and applies it to solve the circular restricted three body problem. This method produces recurrence relations for the coefficients of Taylor Series solutions that can be evaluated numerically or manipulated further to investigate properties of the solution. These recurrence relations are found explicitly in terms of a sequence of derivatives of the state with respect to time. From these derivatives derivatives with respect to other parameters may also be found, including those that describe the dependence of the solution on initial conditions.

**10:20 AAS 18-434 Orbital Maintenance for the Wide Field Infrared Survey Telescope: The Effects of Solar Radiation Pressure and Navigation Accuracies on Station Keeping**

*Ariadna Farres, University of Maryland Baltimore County; David Folta, NASA Goddard Space Flight Center; Cassandra Webster, NASA Goddard Space Flight Center; Jennifer Donaldson, NASA Goddard Space Flight Ceter*

The Wide-Field Infrared Survey Telescope (WFIRST), a NASA observatory designed to investigate dark energy and astrophysics, is planned for a launch in 2025 to orbit the Sun-Earth L2 (SEL2) Libration Point. Due to the instability of the SEL2 vicinity, WFIRST must perform maneuvers to remain in orbit. This paper reviews Floquet based stationkeeping methods that are being taken into account to meet mission requirements. We will describe multiple stationkeeping strategies and explore the possibility of using an on-board navigation system for maneuver data, and finally study how Solar Radiation Pressure (SRP) affects its orbital motion and controllability.

**10:40 AAS 18-447 RAAN-Agnostic 3-Burn Departure Methodology for Deep Space Missions from LEO Depots**

*Michel Loucks, Space Exploration Engineering (SEE); Jonathan Goff, Altius Space*

*Machines; John P. Carrico, Space Exploration Engineering, Inc.; Brian Hardy, Altius Space Machines*

The authors continue investigation of a 3-burn departure approach that enables deep space missions to depart from a LEO depot even if the depot orbital plane is not optimally aligned with the desired departure asymptote. In this paper, a methodology will be described for targeting specific departure trajectories from a LEO depot whose orbit's RAAN is not optimized for the given mission, the impact of LEO depot RAAN-misalignment on delta-V losses and phasing orbit durations will be quantified, and the concept will be illustrated by showing how multiple interplanetary missions can realistically be launched from a single LEO depot.

**11:00 AAS 18-467 A Piecewise-Constant Sundman Transformation for Spacecraft Trajectory Optimization**

*David Ottesen, The University of Texas at Austin; Ryan Russell, The University of Texas at Austin*

Recently, a direct, gradient-based optimization method for spacecraft trajectories was presented that uses embedded boundary value problems to enforce position continuity. The method discretizes a spacecraft trajectory to enable impulsive maneuvers that approximate both unconstrained and low thrust. An equally-spaced discretization in real time is difficult because of varying eccentricities encountered during optimization. As a solution, a piecewise-constant function based on the Sundman transformation is introduced that is simple to implement, enables the use of Lambert solvers, and enforces short segments for all eccentricities. Short segments are fast, robust for boundary value problems, and ensure a better approximate low-thrust model.

**11:20 AAS 18-475 Design and Synthesis of Automatic Powered Descent and Landing Maneuver Trajectories using Motion Envelopes**

*Melissa Onishi, University of Hawaii at Mānoa; Dilmurat Azimov, University of Hawaii at Manoa*

The past NASA landing missions have led to the necessity of designing the next generation of landers with the goal of achieving safe and precise landing. This work presents the results of simulations devoted to formulation of manifolds of the initial and final points connecting the phases along the powered descent and landing trajectory. These manifolds can be formed by a construction of envelopes of the landing trajectories using wide ranges of terminal conditions for the trajectory and lander's parameters.

**11:40 AAS 18-445 Uncertainty Quantification for Mars Entry Using Modified Generalized Polynomial Chaos**

*Xiuqiang Jiang, Nanjing University of Aeronautics and Astronautics; Shuang Li, Nanjing University of Aeronautics and Astronautics; Roberto Furfaro, The University of Arizona*

This paper presents a novel computational approach for quantifying the propagation of uncertainties in state trajectories of low-lift Mars entry vehicle. The unique contribution of this work is twofold: one is considering the change of stochastic characteristics due to the high nonlinearity of Mars entry dynamics to improve propagation accuracy, and the other is suppressing the increase of equation dimension in long-term integration to enhance computational efficiency. Generalized polynomial chaos is modified accordingly through adaptively conducting spectral decomposition and random space decomposition to build a new computational procedure for Mars entry uncertainty quantification.

**Aug 22, 2018 Superior B – Spacecraft GNC – III**

## Wednesday Session 4 Spacecraft GNC-III

Chair: Roberto Furfaro, The University of Arizona
Co-Chair: Kyle DeMars, Missouri University of Science and Technology

**8:00** **AAS 18-291** **Analysis of Uncertainty Propagation in Mars Entry Using Non-Intrusive Polynomial Chaos**
*Xiuqiang Jiang, Nanjing University of Aeronautics and Astronautics; Shuang Li, Nanjing University of Aeronautics and Astronautics*

Uncertainty quantification and propagation is a significant prerequisite and major technical challenge for the development of next generation Mars entry, descent, and landing technologies. Unfortunately, to date, few public reports have explored the uncertainty propagation in Mars atmospheric entry dynamics. In this study, the uncertainty propagation is investigated according to the initial state uncertainty at the entry interface, and the probabilistic quantification of entry trajectory is sought. The uncertainty propagation for Mars atmospheric entry is implemented under non-intrusive polynomial chaos framework.

**8:20** **AAS 18-285** **The F-Radius Sphere Model: Theory and Applications**
*Daniele Mortari, Texas A&M University; Carl Leake, Texas A&M University*

This paper builds on previous research to propose a new model for pin-hole calibrated cameras. The pin-hole model performs gnomonic projection, which creates radial distortion. The proposed method avoids this radial distortion by projecting the observed, spherical 3-dimensional world onto a fictitious spherical imager called the f-radius sphere (FRS). The FRS model is introduced for continuous (infinitesimal pixel size) and discrete (finite pixel dimensions) imagers. The main result of the FRS is the geometric center of a pixel is not necessarily coincident with the "barycenter" of photon flux over the pixel. This model provides the correct "barycenter" location.

**8:40** **AAS 18-253** **Robust Myopic Control for Systems with Imperfect Observations**
*Dantong Ge, Beijing Institute of Technology; Melkior Ornik, University of Texas at Austin; Ufuk Topcu, University of Texas at Austin*

Control of systems operating in unexplored environments is challenging due to lack of complete model knowledge. Additionally, under measurement noises, data collected from onboard sensors are of limited accuracy. This paper considers imperfect state observations in developing a control strategy for systems moving in unknown environments. First, we include hard constraints in the problem for safety concerns. Given the observed states, the robust myopic control approach learns local dynamics, explores all possible trajectories within the observation error bound, and computes the optimal control action using robust optimization. Finally, we validate the method in an OSIRIS-REx-based asteroid landing scenario.

**9:00** **AAS 18-348** **Optimal Libration Control of Space Debris Deorbit Using Space Tug System in Horizontal Configuration**

*Li Pengjie, Beihang University, Beijing, China*

This paper proposes a two-phased optimal control scheme to control libration of space tug system with input of thrust and tether length. The first phase derives the open-loop control trajectory optimization of the input of control system. The second phase deals with the closed-loop optimal control for tracking the derived optimal reference trajectory. The aforementioned cost function minimization problem is solved by a direct solution method. A direct collocation method, based on the Hermite–Simpson scheme, is adopted to discretize the continuous problem.

**9:20** **AAS 18-354** **X-Ray Pulsar Navigation Optimization Using Spherical Partitions**

*Samuel McConnell, Student ; Stoian Borissov, Texas A&M University; Michael McCarthy, Texas A&M University; Ty Buchanan, Texas A&M University; Kevin Tang, Texas A&M University; Monte Wasson, Texas A&M; Anthony Young, TAMU; Daniele Mortari, Texas A&M University*

Due to the periodic nature of pulsars, it is difficult to discern the difference between two pulses from a pulsar. This presents the primary problem for using pulsars as a system of navigation  in which requires constant navigation calculations due to potentially large uncertainties created by stalls in position tracking, which happen soon after leaving earth orbit, after temporary glitches in a spacecraft navigation system, after coming out of a low power sleep mode, etc. We propose a method of dealing with that problem by sectioning off that ambiguous area with spheres to allow for a computationally efficient method of

**9:40** **Break**

**10:00** **AAS 18-379** **Hyperbolic-Tangent-Based Double-Smoothing Method And Its Application In Optimal Control**

*Ehsan Taheri, Texas A&M University; John L. Junkins, Texas A&M University*

Depending on the form of the performance index, the Hamiltonian of a large number of dynamical systems may turn out to be affine in control, where extremal control may switch between the bounds of the admissible set or take on values interior to its admissible set. This paper demonstrates a double-smoothing method capable of capturing sequences of extremal controls such as regular and singular arcs and any combination of them. Application of the method is demonstrated by solving the Goddard rocket problem with a known “bang-singular-bang” control structure and physical insights on singular control are offered through associated singular surface.

**10:20** **AAS 18-412** **Identification of Partially Resolved Objects in Space Imagery with Neural Networks**

*Christopher Ertl, Rensselaer Polytechnic Institute; John Christian, Rensselaer Polytechnic Institute*

There are many scenarios where it may be useful to identify partially resolved space objects in an image and match it to a database of known objects. Through the use of machine learning the objects can be identified at various distances, relative attitudes, and phase angles. In this study, a fully-connected and convolutional neural network are constructed and evaluated. Performance as a function of phase angle and distance are used to evaluate the capability of both neural networks. Multiple neural networks are then trained at overlapping regions of phase angles.

**10:40** **AAS 18-227** **Linear Analysis and Control of a Tethered System with Two Rigid End Bodies**

*Nickolas Sabey, University of Colorado at Colorado Springs; Steven Tragesser, University of Colorado at Colorado Springs*

A model is proposed for studying of the dynamics of a lunar tethered satellite system with identical rigid end-masses with offset tether attachment points, and a massless tether. The system of equations are developed and linearized for use within a linear control system. A linear quadratic regulator paired with a reduced-order closed loop estimator is designed to control the attitude of the end-masses. End-mass oscillation is shown to be approximated by an accelerating rigid pendulum. Two modes of end-mass operation are explored: nadir aligned, and tether aligned. Results show both modes are possible for small libration angles.

**11:00** **AAS 18-290** **Integrated Guidance and Control for Pinpoint Mars Landing using Reinforcement Learning**

*Brian Gaudet, Deep AnalytX, LLC; Richard Linares, University of Minnesota; Roberto Furfaro, The University of Arizona*

In this paper we present a novel integrated guidance and control algorithm designed by applying the principles of reinforcement learning theory. The key innovation is the use of reinforcement learning to learn a policy mapping the lander's estimated state directly to actuator commands, with the policy resulting in accurate and fuel efficient trajectories. Specifically, we use proximal policy optimization, a policy gradient method, to learn the policy. We will present simulation results demonstrating the guidance and control system's performance in a 6-DOF simulation environment, and establish robustness to noise and system parameter uncertainty.

**11:20** **AAS 18-297** **Fuel-Optimal Control Method of Hovering Formation Initialization and Reconfiguration**

*Yinrui Rao, China Academy of Engineering Physics; Huan Chen, School of Astronautics, Beihang University; Chao Han, Beihang University*

A time-constrained fuel-optimal control problem of the hovering formation initialization and reconfiguration is exhaustively researched. Using the relative motion model based on relative orbit elements, a double impulse control equation based on relative Lambert's transfer is derived, which can be applied to solve the hovering formation control problem. In addition, combining the presented equation and the differential evolution algorithm, the time of the two maneuvers and the relative position of the second maneuver are optimized, and the fuel-optimal control strategies for the hovering formation initialization and reconfiguration are obtained. Several numerical simulations are conducted to demonstrate the proposed method's efficacy.

**11:40** **AAS 18-335** **Decentralized Cooperative Localization for a Spacecraft Swarm**
*William Bezouska, University of Southern California*

Future cellular satellite mission architectures will require the ability to determine relative state among the members of spacecraft swarms. This paper proposes a decentralized Multiplicative Extended Kalman Filter-based framework for cooperative localization of a spacecraft swarm. Each spacecraft uses an onboard filter to estimate the relative state (position, velocity, orientation, and angular velocity) of every other spacecraft within the swarm. These estimates fuse onboard gyroscopes and star trackers measurements with relative pose measurements which are sensed directly or shared by the other swarm spacecraft. State estimation performance and computational requirements, as a function of swarm size, are provided.

**Aug 22, 2018 Cirque – Space Situational Awareness – III**

## Wednesday Session 5 Space Situational Awareness-III

Chair: Marcus Holzinger, University of Colorado Boulder
Co-Chair: Jeffrey Stuart, Jet Propulsion Laboratory

**13:30** **AAS 18-427** **Learning Capabilities of Neural Networks and Keplerian Dynamics**
*Damien GUEHO, The Pennsylvania State University; Puneet Singla, Pennsylvania State University; Robert G. Melton, Pennsylvania State University*

Machine learning (ML) tools, especially deep neural networks (DNNs) have garnered significant attention in last one decade. These tools have been used successfully to carry-out operations such as image, speech and text recognition using large set of training data. However, the effectiveness of ML tools in comprehensively representing dynamical models for analysis, prediction and control purposes have not been studied in detail. It is not clear that whether ML tools can learn the inherent characteristic of dynamical model (such as energy conversation, momentum conversation, etc.) from the training data set.

**13:50** **AAS 18-249** **SmallSat Navigation via the Deep Space Network: Inner Solar System Missions**
*Jeffrey Stuart, Jet Propulsion Laboratory; Lincoln Wood, Jet Propulsion Laboratory, Caltech*

The space industry has seen an explosion in the number of operational SmallSats in Earth orbit, with a natural interest in extending SmallSat capabilities outside of low Earth orbit. As with larger missions, near-term deep-space SmallSats will rely on the DSN or similar facilities. Given the predicted growth in the number of deep space missions, effective use of DSN resources will be more critical than ever. Our investigation provides an initial survey of expected inner Solar System navigation performance for DSN radiometric data types, from two-way Doppler and ranging to one-way equivalents, including DDOR and alternate tracking strategies.

**14:10 AAS 18-327 Generalization Capability of Machine Learning Approach Among Different Satellites: Validated Using TLE Data**

*Hao Peng, Rutgers, The State University of New Jersey; Xiaoli Bai, Rutgers*

In previous studies, a machine learning (ML) approach has been proposed to improve orbit prediction accuracy of resident space objects (RSOs), and been investigated using both a simulated environment and the two-line element (TLE) catalog. The ML approach has shown good generalization capabilities from one RSO's historical data to future epochs. In this paper, using TLE data, the generalization capability from one to another RSO will be further investigated. One potential application is that ML models trained by limited number of high-accuracy RSOs can be applied onto other RSOs.

**14:30 AAS 18-403 Multiple Set Filtering Using Probability Hypothesis Densities**

*James McCabe, Missouri University of Science and Technology; Kyle DeMars, Missouri University of Science and Technology*

Emerging tools derived from finite set statistics model candidate targets as a random finite set (RFS) and use Bayesian inference to produce estimates of the RFS given collected data. This work aims to extend that concept to estimating multiple RFSs simultaneously such that targets belonging to different state spaces may be tracked in the same framework. The new filter utilizes the probability hypothesis densities of the RFS to approximate the joint multitarget Bayes filter of the sets. Expressions for the time and measurement update steps are derived, modifications are made to enable practical implementation, and numerical studies are presented.

**14:50 AAS 18-450 Admissible Regions for Low-SNR Doppler Observables of LEO Satellites**

*Andrey Pak, Georgia Institute of Technology; Marcus Holzinger, University of Colorado Boulder*

Precise information of the position of Earth-orbiting object is a crucial activity for Space Situational Awareness. One of the first challenges in the SSA workflow is the process of Initial Orbit Determination (IOD), for which various techniques were developed. This paper contributes to the orbit determination research by exploring the admissible region approach for IOD in a single-station Doppler observation case. The results are then shown and verified for both simulated and real observations. Real scenario considers the observations of Doppler shifts of Low Earth Orbit (LEO) amateur radio satellites in the presence of heavy man-made noise congestion.

**15:10 Break**

**15:30 AAS 18-451 Multiple Hypothesis Tracking and Joint Probabilistic Data Association Filters for Multiple Space Object Tracking**

*Nagavenkat Adurthi, Texas A&M University; Utkarsh Mishra, Texas A&M University; Manoranjan Majji, Texas A&M University, College Station; Puneet Singla, Pennsylvania State University*

In this paper we rewiew the Multiple Hypothesis Tracker (MHT) and the Joint Probabilistic Data Association (JPDA) Filter for tracking Resident Space Objects. Data Association is the problem of associating measurements to targets when the true origin of the measurements is uncertain, such as measurements from debris, false positives and even spurious or enemy sources. We provide a comparative study in terms of accuracy and computational complexity for the MHT and JPDA filters using a typical scenario of tracking multiple space objects with ground based sensors. Further, several approximations to the MHT are discussed to alleviate the computational complexity.

**15:50 AAS 18-471 An Optimization Formulation of Information Theoretic Sensor Tasking**

*Matthew Gualdoni, Missouri University of Science and Technology; Kyle DeMars, Missouri University of Science and Technology*

The use of the Kullback-Leibler divergence as a cost function in sensor tasking applications has been investigated and compared to other measures extensively, including the use of largest Lyapunov exponents and the Fisher information gain, and has been shown to be effective as a means of defining a sensor tasking policy. These approaches have been used to consider multi-observation sets in a sequential manner, meaning they don't necessarily consider the impact a measurement has on the strength of future updates. This work develops optimization surfaces enable the selection of a truly optimal observation set, as well as enable fast optimization

**16:10 AAS 18-216 Systematic Exploration of Solar Gravity Driven Orbital Transfers in the Martian System using Artificial Neural Networks**

*Stijn De Smet, University of Colorado; Daniel Scheeres, University of Colorado at Boulder; Jeff Parker, Advanced Space*

Current solar electric propulsion and launch vehicle technology enables sending multiple spacecraft to Mars simultaneously. For capture orbits with very high apoapse, solar gravity perturbations can deploy the spacecraft into vastly different orbits. The control authority of the Sunon a perturbed capture orbit will be analyzed within the Martian system. Artificial neural networks only require a small set of integrated transfers, while maintaining sufficient accuracy to enable preliminary transfer design. This allows the design of transfers between a low, near polar orbit to for instance Phobos and Deimos in the eccentric Hill model.

**Aug 22, 2018 Superior B – Attitude Dynamics & Control – III**

## Wednesday Session 6 Attitude Dynamics & Control-III

Chair: Atri Dutta, Wichita State University
Co-Chair: Weston Faber, Applied Defense Solutions

**13:30** **AAS 18-334** **Good Performance Above the Bandwidth of a Control System Using Inverse Model Iterative Learning Control**

*Tianyi Zhang, Columbia University; Richard Longman, Columbia University*

Iterative learning control (ILC) seeks to converge to zero tracking error performing a repeated tracking task. The command in the current run is adjusted based on error in the previous run. Spacecraft applications include improving tracking performance of repeated scanning maneuvers of sensors. ILC wants to produce zero error to Nyquist frequency. This paper develops procedures to use the inverse model ILC law to increase the bandwidth of the feedback control system. The simulation shows that the increase from 1.4Hz to 8Hz for robot link..

**13:50** **AAS 18-466** **Precision Attitude Determination for Geosynchronous Orbit Using Extended Kalman Filter with Neuro-Fuzzy Adaptive Tuning**

*Sung-Woo Kim, Satrec Initiative*

This paper presents a precision attitude determination of geosynchronous satellite using an adaptive extended Kalman filter (EKF). The star tracker and gyro measurements are used and the sate vector to be estimated includes satellite attitude and gyro bias. Two different approach is proposed for adaptive tuning of Q and R using adaptive neuro-fuzzy inference system (ANFIS). Initially Q is fixed and R is adapted using ANFIS based on innovation based adaptive estimation (IAE) then the Q is adapted using ANFIS with information of R. The simulation results show higher estimation accuracy of proposed method compared to traditional tuning.

**14:10** **AAS 18-275** **THE NECKLACES STAR ID ALGORITHM**

*Marcio Afonso Arimura Fialho, INPE; David Arnas, Centro Universitario de la Defensa - Zaragoza; Daniele Mortari, Texas A&M University*

Star trackers are essential for almost every space mission with stringent pointing requirements. Their success depends critically on Star-ID algorithms capable of correctly identifying stars in real time even in the presence of tens or hundreds of unavoidable false stars. All this being subject to the speed and memory constraints imposed by the limited embedded computer of a star tracker. With the goal of motivating the development of better algorithms, ESA sponsored in 2017 the 'Star Trackers - First Contact' competition. This paper presents a new star-ID algorithm which is an evolution of the winning algorithm.

**14:50** **AAS 18-479** **Precision Attitude Determination for Spacecraft Formation Flying Using Star Tracker and Vision Navigation System**

*Sung-Woo Kim, Satrec Initiative*

In this paper, a novel approach is presented for relative and absolute attitude determination of spacecraft in a formation flying. This approach is based on measurement fusion between a star tracker and a vision navigation system. Through measurement fusion, a filter is fed more information for state estimation and hence the estimation accuracy get better than the result when the star tracker or the vision navigation system is used solely. The feasibility and the benefit of the approach presented in this paper is verified through formation flying simulation.

**15:10 Break**

**15:30 AAS 18-449 Covariance matching filter for IMU error estimation**

*Rahul Moghe, The University of Texas at Austin; Renato Zanetti, University of Texas at Austin; Maruthi R. Akella, University of Texas at Austin*

In this paper, an on-line adaptive accelerometer calibration algorithm is presented. The accelerometer is corrupted with an exponentially correlated random bias and white Gaussian noise. Assuming the availability of noisy position and velocity measurements, the estimates of position, velocity, bias as well as the accelerometer's noise characteristics are estimated. These results are made possible through the application of use a covariance matching adaptive filter recently established by the authors. Numerical simulations are performed to evaluate the performance of the proposed calibration algorithm and its effectiveness subject to noisy accelerometer measurements.

**15:50 AAS 18-301 ORBIT AND ATTITUDE OBSERVABILITY USING ACCELEROMETER MEASUREMENTS**

*David Geller, Utah State University; Rachit Bhatia, Utah State University*

Under the ideal assumptions of a point mass gravity model and zero non-gravitational accelerations, it is shown that an onboard gravity model and measurements from an accelerometer-based gradiometer consisting of three 3-axis onboard accelerometers can provide simultaneous orbital and attitude observability. Orbital and attitude navigation based on traditional dead-reckoning is not considered. Instead, gravity field gradients from onboard accelerometer measurements are correlated to onboard gravity maps, and used to conduct spacecraft orbital position, velocity and attitude observability analysis. The analysis is extended to higher order gravity models.

**16:10 AAS 18-464 Geomagnetic Field Based Initial Attitude Acquisition of ACADS: A Nano Class Earth Orbiter**

*Karthic Balasubramanian, Team Indus-Axiom Research Labs Private Limited*

The Axiom Capability Demonstration Satellite (ACADS) is nano class spacecraft of 10 kg, equipped with an imaging payload to investigate the Earth by taking images. As the ACADS carries the imaging payload, it dictates Three Axis Stabilization platform. This paper explains the traditional B-Dot control which is exploited to reduce the angular rates of the ACADS, after it is separated from the launcher. The initial worst case rates are considered to be 10 deg/sec. The ADCS uses Three Axis Magnetometer (TAM) and Magnetic Torque Bar (MTB) for the initial attitude acquisition.

## Wednesday Session 7 Mission Design for Spacecraft in Near Rectilinear Halo Orbits

Chair: Kathleen C. Howell, Purdue University
Co-Chair: Ryan Whitley, NASA, Diane Davis, a.i. solutions, Inc.

**13:30** **AAS 18-236** **Analysis of Near Rectilinear Halo Orbit Insertion with a 40-kW-Class Solar Electric Propulsion System**

*Steven McCarty, NASA Glenn Research Center; Laura Burke, NASA Glenn Research Center; Melissa McGuire, NASA GRC; Waldy Sjauw, NASA Glenn Research Center*

This paper examines two low thrust insertion options for delivery of a 40-kW solar electric propulsion (SEP) spacecraft to a Near Rectilinear Halo Orbit (NRHO). The first option considered is to launch as a co-manifested payload on the Space Launch System. A second option considered is to launch on a smaller commercial launch vehicle, to a less energetic elliptical orbit, and use SEP to spiral out to the NRHO. For both options, a number of trades are presented to understand the senstivities of each.

**13:50** **AAS 18-289** **Disposal Trajectories from Near Rectilinear Halo Orbits**

*Kenza Boudad, Purdue University; Diane Davis, a.i. solutions, Inc.; Kathleen C. Howell, Purdue University*

After completion of a resupply mission to NASA's proposed Lunar Orbital Platform – Gateway, safe disposal of the Logistic Module is required. One potential option is disposal to heliocentric space. This investigation includes exploration of the trajectory escape dynamics from an Earth-Moon Near Rectilinear Halo Orbit and applies these findings to the design of a low-cost heliocentric Logistic Module disposal option. The solar gravitational perturbations are investigated in both the Bi-Circular Restricted 4-Body Problem, using the Finite-time Lyapunov Exponent, and in an ephemeris force model.

**14:30** **AAS 18-351** **EXAMINING THE FEASIBILITY OF RELATIVE-ONLY NAVIGATION FOR CREWED MISSIONS TO NEAR RECTILINEAR HALO ORBITS**

*Michael Volle, a.i. solutions, Inc.; Diane Davis, a.i. solutions, Inc.*

Recently, lunar Near Rectilinear Halo Orbits (NRHO) have been the focus of much study, and they have been selected as the target orbit for the Lunar Orbital Platform-Gateway (LOP-G). In this work, the performance of relative-only navigation between a NRHO and a Distant Retrograde Orbit (DRO) is examined and compared to DSN tracking using a Square Root Information Filter (SRIF). Various tracking scenarios are examined using a closed-loop simulation where navigation errors inform maneuver planning and maneuver execution errors affect navigation performance. Results indicate that relative-only navigation can provide comparable levels of orbit determination error and station-keeping costs.

**14:50** **AAS 18-388** **Orbit Maintenance and Attitude Control of Spacecraft in Cislunar Near Rectilinear Halo Orbits**

*Clark Newman, a.i. solutions, Inc.; Diane Davis, a.i. solutions, Inc.; Ryan Whitley, NASA; Joseph Guinn, NASA / Caltech JPL; Mark Ryne, NASA / Caltech JPL*

NASA's Lunar Orbital Platform-Gateway will serve as a multi-mission staging ground in cislunar space from a Near-Rectilinear Halo Orbit. It will maintain this orbit with maneuvers near apolune when required. Orbit determination performance is analyzed to determine DSN tracking requirements and sensitivity to navigation error sources. Attitude control considerations are integrated with the orbit maintenance process for uncrewed and crewed configurations. A Solar Pressure Equilibrium Attitude is defined, and slews to/from the maintenance maneuver direction are simulated to investigate attitude control system performance. Translational and rotational perturbations from Orion docking plume impingements are investigated for radial and axial docking configurations.

**15:10** **Break**

**15:30** **AAS 18-406** **Earth-Moon Near Rectilinear Halo and Butterfly Orbits for Lunar Surface Exploration**

*Ryan Whitley, NASA; Diane Davis, a.i. solutions, Inc.; Laura Burke, NASA Glenn Research Center; Brian McCarthy; Rolfe Power, Purdue University; Melissa McGuire, NASA GRC; Kathleen C. Howell, Purdue University*

NASA is planning the next phase of crewed spaceflight with a set of missions designed to establish a human-tended presence beyond low Earth orbit. The current investigation focuses on the staging post potential of cislunar infrastructure by seeking to maximize performance capabilities by optimizing transits in the lunar vicinity for both crewed and robotic spacecraft. In this paper, the current reference orbit for the cislunar architecture, known as a Near Rectilinear Halo Orbit (NRHO), is examined alongside the bifurcated L2 butterfly family for their use as a staging location to the lunar surface.

**15:50** **AAS 18-421** **Analysis of Cislunar Transfers from a Near Rectilinear Halo Orbit with High Power Solar Electric Propulsion**

*Steven McCarty, NASA Glenn Research Center; Laura Burke, NASA Glenn Research Center; Melissa McGuire, NASA GRC*

This paper captures ongoing analysis completed in an effort to design efficient cislunar transfers of a massive spacecraft from an L2 Southern NRHO to a Distant Retrograde Orbit, L1 Northern NRHO, and Flat L2 Halo Orbit using solar electric propulsion (SEP). For each destination orbit, a reference transfer is designed for an assumed spacecraft configuration. For each reference transfer, analysis is completed to understand the sensitivity of the transfer to changes spacecraft acceleration, and to identify the optimal number of thrusters to use for a given combination of mass and power.

## Aug 22, 2018 Superior A – Town Hall Meeting: Astrodynamics Research Funding

### Wednesday Session 8 Town Hall Meeting: Astrodynamics Research Funding

Chair: Nathan Strange, NASA / JPL

**19:30** **AAS 18-490** **Town Hall Meeting: Astrodynamics Research Funding**
*Nathan Strange, NASA / JPL*

This discussion will target the upcoming 2021 release of the National Academies Planetary Science Decadal Survey. These decadal surveys strongly influence NASA's technology investment roadmaps and this upcoming survey provides an opportunity to develop new funding sources for research relevant to Solar System exploration and planetary science.

# Thursday August 23, 2018

**Aug 23, 2018 Maybird – Trajectory Design & Optimization V**

### Thursday Session 1 Trajectory Design & Optimization-V

Chair: Richard Linares, University of Minnesota
Co-Chair: Ehsan Taheri, Texas A&M University

**8:00** **AAS 18-385** **State Vector Representations for Low-Thrust Trajectory Optimization**
*John L. Junkins, Texas A&M University; Ehsan Taheri, Texas A&M University*

Coordinate choices have significant consequences in the analytical and computational approaches to celestial mechanics problems. This paper focuses on the impact of various coordinate representations of the dynamics on the solution of the ensuing two-point boundary-value problems of the indirect formulation of optimal control problems. The relative merits of eight coordinate/element choices are studied: Cartesian, spherical, equinoctial elements and a six element set consisting of the angular momentum vector and the eccentricity vector, and four hybrid coordinate sets associated with an osculating triad defined by the instantaneous position and velocity vectors. The results are interesting and of significant practical utility.

**8:20** **AAS 18-454** **ASTEROID RENDEZVOUS MANEUVER DESIGN CONSIDERING UNCERTAINTY**
*Marco Balducci, CCAR - CU Boulder; Brandon Jones, University of Texas at Austin*

When designing a maneuver for a rendezvous in space, many current methods assume a deterministic system. That is, statistics or uncertainty within the system are either simplified using a method such as linearization or left unquantified. This paper presents the case of an asteroid rendezvous while considering the propagated uncertainty of the asteroid and an approaching spacecraft. Using the surrogate method of separated representations, the uncertainty is efficiently propagated and utilized in an optimization under uncertainty algorithm which allows for variations in the maneuver components. From this, a tractable means of designing a rendezvous maneuver under uncertain conditions is formulated.

**9:00** **AAS 18-392** **Aeropropcapture: Applying Propulsion to Aerocapture Maneuvers**

*Eiji Shibata, AirSat Engineering*

Aeropropcapture (APC) is an atmospheric maneuver that combines aerocapture and chemical propulsion by using a thrusting force in the atmosphere to control the amount of time a spacecraft experiences drag. The capability of APC is first evaluated by looking at trajectories that use only thrust or lift and finding an approximately equivalent lift-to-drag ratio in an aerocapture trajectory for a given entry thrust-to-weight ratio in an APC trajectory. Optimal control problems for APC are then solved by finding the control law for the thrust angle and mangitude for an extremal altitude case.

**9:20** **AAS 18-282** **THE THEORY OF CONNECTIONS APPLIED TO PERTURBED LAMBERT'S PROBLEM**

*Hunter Johnston, Texas A&M University; Daniele Mortari, Texas A&M University*

This paper provides an analytical solution of the perturbed Lambert problem using the "Theory of Connections" (ToC). First, Lambert's problem is solved for the unperturbed case providing the Kepler solution to the equation of motion. Then using ToC, all perturbations are considered simultaneously, and a new perturbed trajectory is solved for using an iterative least-squares technique. Current results produce a trajectory with sub-meter accuracy. Although the perturbed Lambert problem is presented, the methodology in this paper can be applied to an entire class of problems with known unperturbed solutions, where the perturbed solution is "sufficiently close" to the unperturbed one.

**9:40** **Break**

**10:00** **AAS 18-407** **Autonomous Optical Navigation using Nanosatellite-Class Instruments: a Sensor Design Case Study**

*Harry Zhang, Ryerson University; John Enright, Ryerson University*

Spurred by scores of successful missions, the development of nanosatellites has become a growing part of modern technology in recent years. However, interplanetary small satellite missions may not justify the expense of frequent ground tracking. With this being the case, autonomy becomes a valuable asset in a smallsat's capabilities. In previous work we presented an EFK based navigation framework for autonomous orbit determination for nanosats using optical navigation techniques. Using this framework as a basis, this paper looks to optimize the sensor configuration for the system. Mounting angle, field of view size, and sensor quantity are parameters of consideration.

**10:40 AAS 18-457 Mars Aerocapture and Subsystems Analysis for a Cycler Orbit Crew Transfer Vehicle**

*Larissa Balestrero Machado, Florida Institute of Technology; Markus Wilde, Florida Institute of Technology; Brian Kaplinger, Florida Institute of Technology; Robert Moses, NASA Langley Research Center*

This paper presents the results of a vehicle conceptual design and aerocapture analysis for a Crew Transfer Vehicle to/from a Mars Cycler Orbit. The requirements for the vehicle are dependent on the ability of the vehicle to effectively aerocapture or to capture at Mars using combined aerodynamic and propulsive braking. For different classes of cycler orbits, the speed of interaction with Mars influences the Crew Transfer Vehicle design through the aerocapture phase. Concepts for the integration of this phases with a sustainable cycler architecture are presented.

**11:00 AAS 18-395 Adaptive ZEM/ZEV Guidance For Halo Orbit Insertion In The Circular Restricted Three-Body Problem**

*Kristofer Drozd, University of Arizona; Roberto Furfaro, The University of Arizona; Francesco Topputo, Politecnico di Milano; Andrea Scorsoglio, Politechnico di Milano; Richard Linares, University of Minnesota*

This paper presents an adaptive ZEM/ZEV guidance algorithm capable of generating closed-loop quasi-optimal trajectories for halo transfer in the Circular Restricted Three Body dynamics. The approach employs a reinforcement learning framework to adapt the guidance gains via an Actor-Critic algorithm based on a combination of stochastic gradient descent and extreme learning machines. The proposed methodology greatly expands the capabilities of classical ZEM/ZEV guidance, allowing for its use in a wide variety of environment and constraint combinations, giving results that are generally close to the constrained fuel optimal off-line solution.

## Aug 23, 2018 Cirque – Space Situational Awareness – IV

### Thursday Session 2 Space Situational Awareness-IV

Chair: Islam Hussein, Applied Defense Solutions
Co-Chair: Jacob Darling, Air Force Research Laboratory

**8:00 AAS 18-260 LOW-EARTH ORBIT DETERMINATION BASED ON ATMOSPHERIC DRAG MEASUREMENTS**

*Rui Zhang, Beihang University; Fei Xu, Institute of Army Aviation; Chao Han, Beihang University; Xiucong Sun*

An autonomous low-Earth orbit determination method based on measurements of atmospheric drag with use of a high-precision tri-axis accelerometer as well as a star sensor is proposed. A set of equations is formulated to obtain the six orbital elements from drag measurements at two epochs, and analytical solution of initial values is provided under the assumption of near-circular orbit. Numerical simulations show good performance of the new orbit determination method, which is useful for navigation of low-Earth-orbiting spacecraft in non-GNSS environments.

**8:20** **AAS 18-393** **Polynomial Chaos on the Unit Circle**
*Christine Schmid, Missouri University of Science and Technology; Kyle DeMars, Missouri University of Science and Technology*

Polynomial chaos expresses a probability density function (pdf) as a linear combination of basis polynomials. If the density and basis polynomials are over the same field, any set of basis polynomials can describe the pdf; however, the most logical choice of polynomials is the family that is orthogonal with respect to the pdf. This problem is well-studied over the field of real numbers, but has yet to be extended to the field of complex numbers. This extension is presented for angular random variables, which are confined to the complex unit circle.

**9:20** **AAS 18-440** **Multi-Target Tracking and Conjunction Assessment for Large Constellations**
*Nicholas Ravago, The University of Texas at Austin; Brandon Jones, University of Texas at Austin*

Recently proposed constellations of thousands of telecommunications satellites present an operational risk to LEO satellites and could accelerate space debris growth. Precise and efficient tracking methods will be needed for safe operations. This paper proposes an integrated sensor tasking and tracking algorithm for large constellations. The tasking algorithm uses an information theoretic reward function to efficiently allocate tasks to sensors. The data is processed used the Labeled Multi-Bernoulli (LMB) filter. System efficacy is demonstrated by tracking a constellation of 4,425 satellites from a network of six ground sensors and using the results to perform a conjunction analysis.

**9:40** **Break**

**10:00** **AAS 18-292** **Atmospheric Mass Density Calibration and its Application in LEO Object Orbit Prediction Using Angular Data from a Small-telescope Array**
*Junyu Chen, Wuhan University; Sang Jizhang*

This paper presents results of atmospheric density calibration and its effect on orbit prediction using angular data collected by a small-telescope array. The HASDM method and atmospheric density model coefficient (ADMC) modification method are applied to calibrate the density using tracking data of objects in the height region from 380 to 600km. It is found that, the 7-day OP errors are reduced by about 50% when the calibrated density is used in the orbit predictions of the objects in the calibration region, and the OP errors for the objects outside the calibration region are reduced by about 30%.

**10:20** **AAS 18-328** **Obtain Confidence Interval for The Machine Learning Approach to Improve Orbit Prediction Accuracy**
*Hao Peng, Rutgers, The State University of New Jersey; Xiaoli Bai, Rutgers*

In previous studies, a machine learning (ML) approach has been proposed to improve orbit prediction accuracy of resident space objects (RSOs), and been validated using both simulated and real data. In this paper, the ML approach will be further developed to provide confidence intervals of its predictions. Specifically, by introducing Gaussian process regression (GPR) model into the ML approach, the ML approach could generate both a predicted mean value and its corresponding confidence interval. The dependence of the GPR model's performance on kernel functions, learning variables, and training data size will also be discussed in detail.

**10:40** **AAS 18-235** **Space Debris Field Removal Using Tether Momentum Exchange**

*Zachary Asher, Western Michigan University; Steven Tragesser, University of Colorado at Colorado Springs; Christian Kneubel, University of Michigan; Jennifer Hudson, Western Michigan University; Thomas Bradley, Colorado State University; Ilya Kolmanovsky, University of Michigan*

This research argues feasibility of sequential space debris removal using a single spacecraft by demonstrating removal of a real debris field consisting of 10 debris objects without the use of propellant. The debris objects are removed in order and in real time with only the assumption of in-plane alignment to keep the problem constrained in two dimensions. The methodology governing tether momentum exchange as well as the techniques for sequential debris removal in real time are presented. The results show that with debris planning, removal of hundreds of debris objects without propellant expenditure is possible.

**Aug 23, 2018 Superior A – Astrodynamics – IV**

## Thursday Session 3 Astrodynamics-IV

Chair: Atri Dutta, Wichita State University
Co-Chair: Bharat Mahajan, Odyssey Space Research

**8:00** **AAS 18-207** **Designing LEO Constellations to Minimize Max Revisit Time**

*Thomas Lang, The Aerospace Corp*

Designing optimal constellations to provide continuous global coverage has become a table-look-up exercise. While allowing coverage gaps or “revisit times” can significantly reduce the constellation size, there has been no correspondingly simple means of finding a LEO constellation which minimizes the maximum revisit time (MRT). This paper shows that a simple table-look-up method is possible using optimized “regular” LEO constellations. These optimized constellations give the same values of MRT regardless of LEO altitude, if the MRT is measured in revs (i.e. normalized by the orbit period). Tables of optimized constellations are provided.

**8:20** **AAS 18-288** **A Semi-Analytical Approach to Satellite Constellation Design for Regional Coverage**

*Hang Woon Lee, University of Illinois at Urbana-Champaign; Koki Ho, University of Illinois, Urbana-Champaign; Seiichi Shimizu, Advanced Technology R&D Center, Mitsubishi Electric Corporation; Shoji Yoshikawa, Advanced Technology R&D Center, Mitsubishi Electric Corporation*

This paper introduces a fast and computationally efficient semi-analytical approach to design regional coverage satellite constellations. By fully utilizing the characteristics of the repeating ground track orbits and multiple access intervals between the target and the satellite, the method aims to optimally design satellite constellation with the fewest number of satellites possible. A case study will be performed to demonstrate the value provided by the proposed approach.

**8:40** **AAS 18-344** **Refined Mission Analysis for HERACLES – A Robotic Lunar Surface Sample Return Mission Utilizing Human Infrastructure**

*Florian Renk, European Space Agency; Markus Landgraf, European Space Agency; Lorenzo Bucci, Politecnico di Milano*

In the frame of the International Space Exploration Coordination Working Group the European Space Agency is participating in the planning of future exploration architectures. The mission concept for this robotic lander mission (Human Enhanced Robotic Architecture and Capabilities for Lunar Exploration and Science – HERACLES) has matured meanwhile and this paper shall provide an update on the current mission design as agreed between the international partners and the associated mission analysis as all the intermediate and final orbits have been selected for the baseline.

**9:00** **AAS 18-460** **Quasi-hovering Formation in Elliptical Reference Orbit**

*Huan Chen, School of Astronautics, Beihang University; Chao Han, Beihang University; Yinrui Rao, China Academy of Engineering Physics; Jianfeng Yin, China Academy of Space Technology*

This paper proposes a kind of quasi-hovering formation by forcing the deputy satellite revisiting the same point with impulses. The revisiting formation solution, geometrical properties regarding time, the geometric design method and the maintenance control strategy are investigated in detail. In addition, the optimal control model of quasi-hovering formation is established and simplified to make it easier to solve with dynamic programming algorithm. Finally, numerical examples are conducted to compare the formation maintenance fuel cost of the revisiting formation, the optimal quasi-hovering formation and the strict hovering formation.

**9:20** **AAS 18-425** **Sensor Tasking for Satellite Tracking Utilizing Observability Measures**

*Mitchel McDonald, University of Texas at Arlington; Kamesh Subbarao, University of Texas at Arlington*

This paper presents a new observability measure based sensor tasking method for satellite tracking. The tasking is performed by first computing the Hellinger Distance between ground/space based sensors and space objects and then using this metric for selecting the sensors that maximize observability. The object's state estimates are obtained using nonlinear estimation techniques. The Extended Kalman Filter and Unscented Kalman Filter are compared within this framework. Representative numerical simulations are performed to evaluate the efficacy of the new tasking approach. The proposed tasking approach is also compared with some baseline approaches.

**9:40 Break**

**10:00 AAS 18-486 Supersonic Retropropulsion on Robotic Mars Landers: Selected Design Trades**

*Aron Wolf, Jet Propulsion Laboratory*

Many concepts for future robotic Mars landers require landing heavier payloads. Mars landers to date have used a parachute to help decelerate; however its effectiveness is diminished with heavier payloads, motivating considering eliminating the parachute and initiating powered descent at supersonic speeds (Supersonic Retropropulsion, or SRP). SRP increases the propellant requirement, but also allows significant increases in entry and payload masses. This work investigates the propellant requirement for a notional SRP lander with representative EDL dispersions, for a legacy entry capsule using RCS thrusters for roll control, and for an alternative concept using aerodynamic surfaces for angle-of-attack and yaw control.

**10:20 AAS 18-487 Morphing Hypersonic Waverider Constrained Optimization for Atmospheric Entry**

*Jesse Maxwell, U.S. Naval Research Laboratory*

Prior work has demonstrated the capability of waverider geometry with a flexible, actuated lower surface to enable on-design performance across a range of Mach number [1], the capability to out-perform a conventional atmospheric entry vehicle has been demonstrated [2], and stream surface morphing methodologies for on-design performance and full aerodynamic control [3]. The models and methods are utilized in the present study as an extension of these prior efforts with an emphasis on optimization for minimizing peak heat flux and deceleration in comparison to a conventional reference entry vehicle.

**10:40 AAS 18-343 Designing a Low-Cost, Small-Scale Mars Mission with Orbit Determination Tool Kit**

*Lisa Policastri, Space Exploration Engineering (SEE); James Woodburn, Analytical Graphics, Inc.; John P. Carrico, Space Exploration Engineering, Inc.*

The authors have investigated alternative methods to replace the two-way transponder and USO with low-cost, small-size transceivers without a USO, for flying a Mars mission. Analytical Graphics' (AGI) Orbit Determination Tool Kit (ODTK) is used to simulate a variety of scenarios using only Delta Differential One-way Range (DDOR) and one-way Doppler, for navigation during the Mars cruise, Mars orbit insertion, and a notional Martian science orbit. The Mars 2020 arrival opportunity is used as a baseline case for this research, along with a higher altitude orbit insertion for science operations.