AAS/AIAA Astrodynamics Specialist Conference

9-13 August 2009, Pittsburgh, PA

Conference Program

AAS General Chair
Dr. Ken Chan
The Aerospace Corporation

AIAA General Chair
Dr. L. Alberto Cangahuala
Jet Propulsion Laboratory

AAS Technical Chair
Dr. Anil V. Rao
University of Florida

AIAA Technical Chair
Dr. T. Alan Lovell
AFRL/VSES

American Astronautical Society

American Institute of Aeronautics and Astronautics

Cover images include the spacecraft that are actively orbiting or *en route* to the Moon at the time of this conference. In clockwise order from top left:

- Chandrayaan-1
- Lunar Reconnaissance Orbiter (LRO)
- Artemis
- Lunar Crater Observation and Sensing Satellite (LCROSS)

Cover design by David Fuller

TABLE OF CONTENTS

2009 ASTRODYNAMICS SPECIALIST CONFERENCE INFORMATION

REGISTRATION

Registration Site (https://events.pxi.com/aas/reg)

In order to encourage early registration, we have implemented the following conference registration rate structure: **Register by 1 Aug 2009 and save $50!**

Category	Early Registration (through 1 Aug 2009)	Late Registration
Full - AAS or AIAA Member	$450	$500
Full - Non-member	$535	$585
Retired*	$130	$180
Student*	$130	$180

The receptions are included for all registrants. The Tuesday night Awards Banquet is included only for Full registration fees; Banquet tickets and reception tickets can be purchased on-site for $50 per ticket.

On-site packet pick up and registration will be available on the following schedule:

- Sunday Aug. 9 — 3:00 PM - 06:00 PM
- Monday Aug. 10 — 8:00 AM - 02:00 PM
- Tuesday Aug. 11 — 8:00 AM - 02:00 PM
- Wednesday Aug. 12 — 8:00 AM - 02:00 PM
- Thursday Aug. 13 — 8:00 AM - 10:00 AM

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

Schedule of Events

Day	Start	End	Function	Room
Sun. 9 Aug.	1pm	~5pm	Pirates/Cardinals Baseball Game	PNC Park
	2pm	8pm	Registration	Symphony Foyer
	6pm	9:30pm	Early Bird Reception	Symphony Ballroom

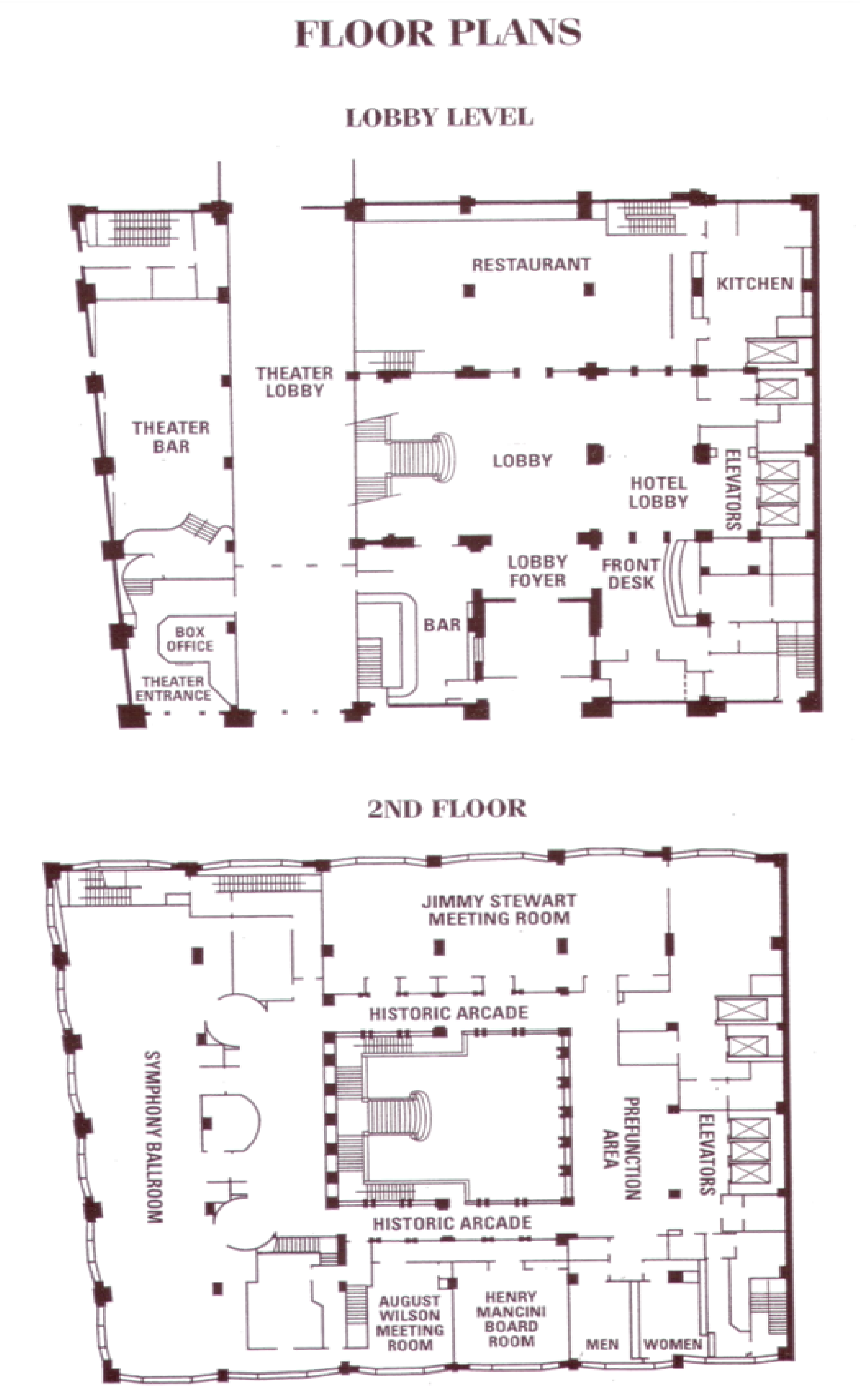
Day	Start	End	Function	Room
Monday 10 August	7am	8am	Speakers Breakfast	Jimmy Stewart
	8am	11:45am	Session 1: Orbit Determination	Symphony A
	8am	11:45am	Session 2: Attitude Dynamics, Determination, and Control I	Symphony B
	8am	11:45am	Session 3: Rendezvous, Relative Motion, and Proximity Missions	Symphony C
	9:40am	10:05am	Morning Break	Symphony Foyer
	Noon	1:30pm	Joint Technical Committee Lunch	Jimmy Stewart
	1:30pm	**5:40pm**	Session 4: Special Session: Flight Dynamics for Magnetospheric Survey Missions	Symphony A
	1:30pm	5:15pm	Session 5: Trajectory Optimization I	Symphony B
	1:30pm	5:15pm	Session 6: Orbital Dynamics I	Symphony C
	3:10pm	3:35pm	Afternoon Break	Symphony Foyer
	5:45pm	6:45pm	Conference Administration Subcommittee	Symphony B
	5:45pm	6:45pm	Technical Administration Subcommittee	Symphony C

Day	Start	End	Function	Room
Tuesday 11 August	7am	8am	Speakers Breakfast	Jimmy Stewart
	8am	11:45am	Session 7: Planetary, Asteroid, and Deep Space Missions I	Symphony A
	8am	11:45am	Session 8: Special Session: Outer Planet Flagship Mission	Symphony B
	8am	11:45am	Session 9: Spacecraft Guidance, Navigation, and Control I	Symphony C
	9:40am	10:05am	Morning Break	Symphony Foyer
	Noon	1:30pm	AAS Spaceflight Mechanics Committee Lunch	Jimmy Stewart
	1:30pm	5:15pm	Session 10: Conjunction Assessment I	Symphony A
	1:30pm	5:15pm	Session 11: Trajectory Optimization II	Symphony B
	3:10pm	3:35pm	Afternoon Break	Symphony Foyer
	5pm	6pm	NRC Planetary Science Decadal Survey White Paper Call, Discussion	Symphony B
	5pm	6pm	Website Administration Subcommittee	Symphony C
	6pm	7pm	Reception	Symphony Foyer
	7pm	10pm	Awards Banquet	Symphony Ballroom

Day	Start	End	Function	Room
Wednesday 12 August	7am	8am	Speakers Breakfast	Jimmy Stewart
	8am	11:45am	Session 12: Attitude Dynamics, Determination, and Control II	Symphony A
	8am	11:45am	Session 13: Formation Flying	Symphony B
	8am	11:45am	Session 14: Dynamical Systems Theory Applied to Space Flight	Symphony C
	9:40am	10:05am	Morning Break	Symphony Foyer
	Noon	1:30pm	AIAA Astrodynamics Technical Committee Lunch	Jimmy Stewart
	1:30pm	5:15pm	Session 15: Spacecraft Guidance, Navigation, and Control II	Symphony A
	1:30pm	5:15pm	Session 16: Conjunction assessment II	Symphony B
	1:30pm	5:15pm	Session 17: Satellite Constellations/Tethered Satellites	Symphony C
	3:10pm	3:35pm	Afternoon Break	Symphony Foyer
	6pm	9pm	Farewell Reception	Rhapsody Ballroom

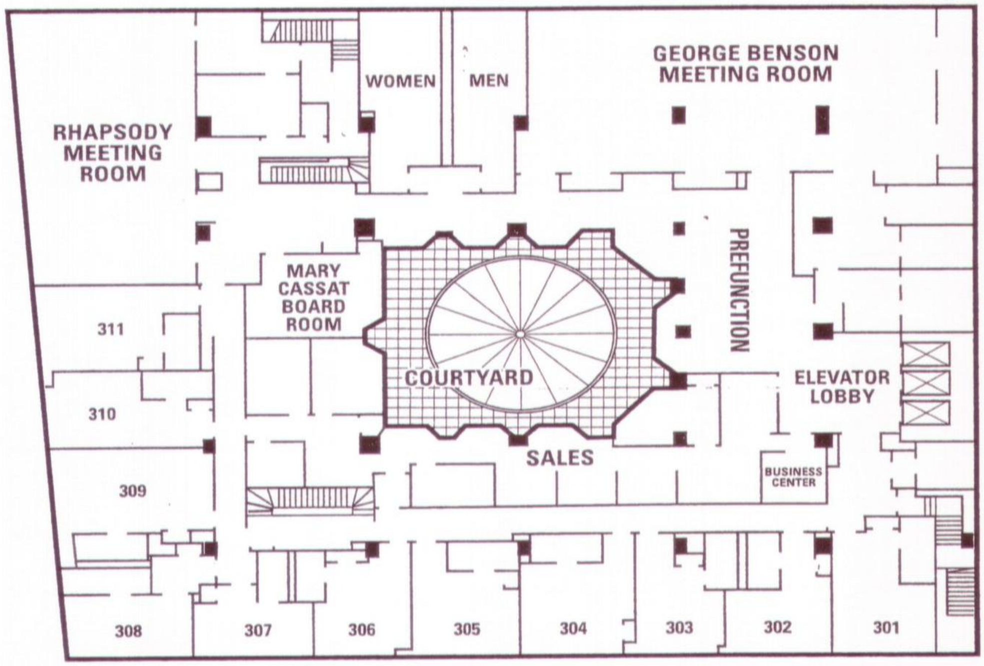
Day	Start	End	Function	Room
Thursday 13 August	7am	8am	Speakers Breakfast	Jimmy Stewart
	8am	11:45am	Session 18: Trajectory Optimization III	Symphony A
	8am	11:45am	Session 19: Planetary, Asteroid, and Deep Space Missions II	Symphony B
	8am	11:45am	Session 20: Orbital Dynamics II	Symphony C
	10am	10:30am	Morning Break	Symphony Foyer

RENAISSANCE HOTEL LAYOUT

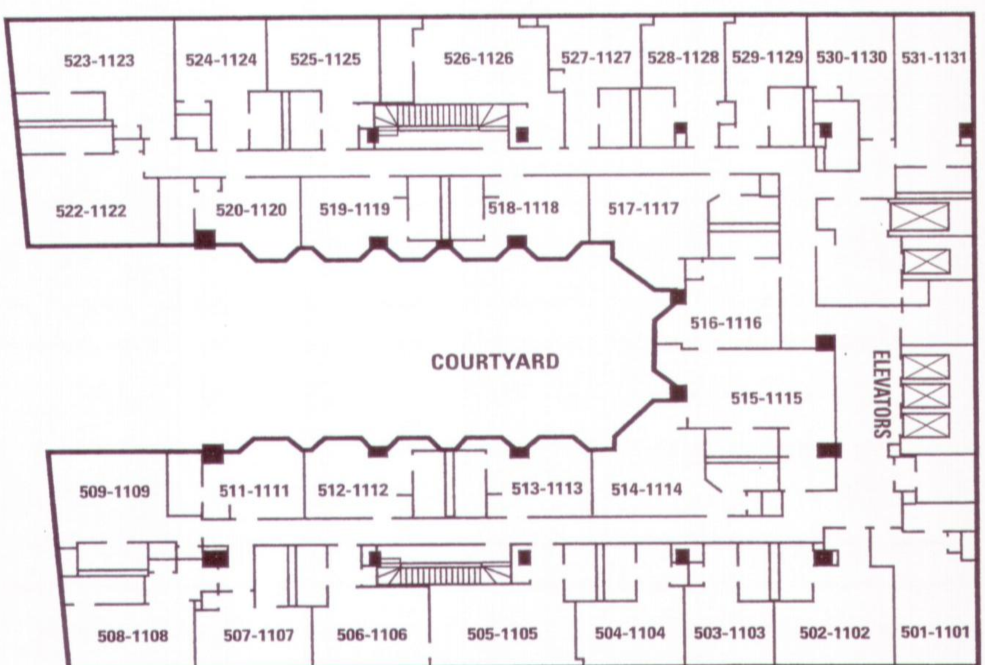


FLOOR PLANS

3RD FLOOR



5-11 FLOORS



Special Events

Pirates / Cardinals Baseball Game

On Sunday we will have a group outing to PNC Park (across the river, one block from the hotel) to see the Pirates play the St. Louis Cardinals. It's a Kids' Day game - kids get a Back-to-School bag and get the opportunity to run the bases down on the field after the game, and all conference members purchasing tickets will get a cap as well (contact Angela Criscella at the Pittsburgh Pirates (angela.criscella@pirates.com; 412.325.4798) before 24 July).

Early Bird Reception

Sunday, 9 August 6 – 9:30pm
Location: Symphony Ballroom

NRC Planetary Science Decadal Survey White Paper Call and Discussion

Tuesday, 11 August 5-6pm
Location: Symphony B

The Space Studies Board of the National Academies is beginning a Planetary Science Decadal Survey that will recommend priorities for planetary science exploration in the interval 2013-2022. As part of the charter of the decadal survey panels, they will identify "strategic technology development needs and opportunities." The panels are accepting community white papers until September 15, 2009.

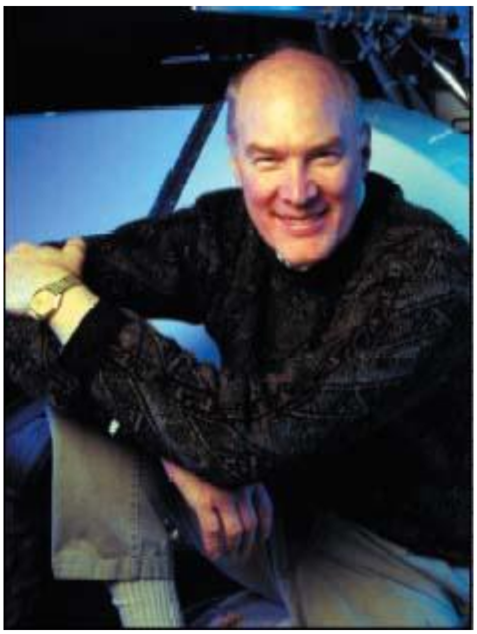
Nathan Strange of JPL will lead an overview of the decadal survey process on Tuesday, 11 August, in Symphony B from 5-5:30pm. This briefing is intended to trigger discussions to organize white papers that we can submit from the astrodynamics community to describe and recommend funding for astrodynamics research and analysis that would have a positive impact on planetary science missions.

AWARDS BANQUET

Tuesday, 11 August	6-7pm Reception, 7-10pm Dinner/Program
Location (Reception)	Symphony Foyer
Location (Awards/Address)	Symphony Ballroom

- ***Breakwell Student Awards***
- ***AIAA Sustained Service Award Presentation***

Featured Speaker – Red Whittaker, Carnegie-Mellon University



William "Red" Whittaker is the Fredkin professor of robotics at Carnegie Mellon University's Robotics Institute. He has developed dozens of robots, breaking new ground in autonomous vehicles, field robotics, space exploration, mining and agriculture. He developed the robots that cleaned up the Three-Mile Island nuclear accident. His ground vehicles have driven thousands of autonomous miles. Whittaker won DARPA's $2 million Urban Challenge. His HUMVEEs finished second and third in DARPA's Grand Challenge desert race.

Whittaker is now competing for the $20-million Google Lunar X PRIZE for privately landing a robot on the moon, which is the topic of his presentation this evening.

Whittaker is a member of the National Academy of Engineering. He is a fellow of the American Association for Artificial Intelligence, and served on the National Academy of Sciences Space Studies Board. Science Digest named Whittaker one of the top 100 U.S. innovators for his work in robotics. He has been recognized by Aviation Week & Space Technology and Design News magazines for outstanding achievement. Fortune named him a “Hero of U.S. Manufacturing”. Whittaker received the Alan Newell Medal for Research Excellence. He received the Teare Award for teaching excellence. He received the Joseph Engelberger Award for outstanding achievement in robotics.

FAREWELL RECEPTION

Wednesday, 12 August	6 – 9pm
Location:	Rhapsody Ballroom

CONFERENCE LOCATION

RENAISSANCE HOTEL ACCOMMODATIONS

The conference is located at the Renaissance Pittsburgh Hotel in Downtown Pittsburgh, PA.

Renaissance Pittsburgh Hotel
107 6th Street
Pittsburgh, PA 15222
Phone: 1-412-562-1200
Reservations: 1-866-454-4400
Fax: 1-412-992-2010
Toll-free: 1-800-468-3571

http://www.marriott.com/hotels/travel/pitbr-renaissance-pittsburgh-hotel/

The Conference rate for the five days of the conference (and three pre- and post-conference days) is $114 plus 14% for current state and local taxes. This rate represents 100% of the federal government lodging per diem. Please request the AAS/AIAA Astrodynamics Specialist Conference rate. (The deadline for securing the conference rate at the hotel was 15 July.)

Attendees should make reservations directly with Marriott reservations (a) at the Renaissance Pittsburgh Hotel at 1-866-454-4400, or (b) online at the Marriott website at the same prevailing government rate and at no extra charges. All reservations must be accompanied by a first night room deposit or guaranteed with a major credit card. This hotel has a smoke-free policy.

Hotel check-in/check-out times at the Renaissance are **4:00pm** and **12:00 Noon**, respectively. Early arrivals may be requested; to guarantee an early arrival, the reservation must be secured for the night prior.

Guest Information

General Room Amenities (may vary by room type)
- Air conditioning
- Alarm clock
- Bottled water
- Coffee maker/tea service
- Crib
- Electrical adapters
- Individual climate control
- Internet browser/Web TV
- Iron and ironing board
- Rollaway bed
- Safe
- Bathrobe, Hair dryer

Room Entertainment
- Cable channel: CNN, ESPN, HBO
- Cable/satellite TV
- Mini-bar
- Movies/videos, pay-per-view
- Video games and players for rent

Business Amenities
- Electrical outlet: desk level
- Phone feature: cordless
- Phone feature: speakerphone
- Phone feature: voice mail
- Two-line phone

Guest Services
- Concierge desk
- Full-service business center
- Room service, 6:00 AM-11:00 PM
- Safe deposit boxes, front desk

Complimentary Services
- Coffee in lobby
- Coffee/tea in-room
- Phone calls: toll-free
- Shoeshine
- On-site Fitness Center
- Gold's Gym Pass

High-speed Internet access
- Public Areas (Wired, Wireless)
- Guest Rooms (Wired, Wireless)
- Meeting Rooms (Wired, Wireless)

Recreation Activities
- Biking/jogging/fitness trail (0.1 miles)
- Bowling (1.1 miles)
- Fly-fishing (1 miles)
- Hiking, nature preserve, trail
- Horseback riding (8 miles)
- Hunting
- Kayaking (0.1 miles)

Golf
- Quicksilver Golf Club(19 miles)
- Hickory Heights Golf Club(12 miles)
- Grand View Golf Club(5 miles)
- Oakmont East(15 miles)
- Lindenwood(14 miles)

Spa
- The Verve 360 of Wellness (appointment required)

Alternate Accommodations

Other Downtown Pittsburgh area accommodations can be found through the following web sites:

http://www.visitpittsburgh.com/sleep
http://www.google.com/maps?f=q&source=s_q&hl=en&geocode=&q=pittsburgh+hotels

GETTING THERE

Directions from Pittsburgh Intl Airport (PIT) to Hotel (18 miles)

- From the airport take PA 60 S., which becomes US 22/30 E and then becomes I-279 N.
- Continue to Pittsburgh through the Fort Pitt Tunnel onto the Fort Pitt Bridge.
- Take the Liberty Avenue exit and proceed down ramp staying straight onto Liberty Avenue.
- Continue to 6th Street and Liberty Avenue intersection, turn left onto 6th Street.
- The hotel is located 2 blocks down on the right.

Estimated taxi fare: 45.00 USD (one-way).

Airport shuttle/limo options are available at

- Express Shuttle USA 412-321-4990 with one-way fare of $19.
- Lenzner Coach USA (Contact: Michelle Santry),
  - Direct 412-749-4158
  - Fax 412-749-4176
  - 1-800-342-2349 Ext. 4158
- Regency Transportation (limo) (http://www.regencytransportation.com)

Still more options at http://www.flypittsburgh.com.

PARKING

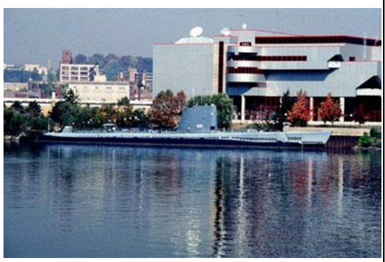
- ***Valet parking rates:***
  - 0 – 4 hours $12
  - 4 – 6 hours $15
  - 6 – 8 hours $18
  - Over 8 hours $25
- ***Off-site parking***: Contact hotel for details.
- ***Self Parking***: There is a city parking garage across the street. No 'in/out' privileges.
  - Day Rate Charges (Monday - Friday, 6:00 am to 3:59 pm)
    - 1 Hour or Less $3.75
    - 2 Hours or Less $4.75
    - 4 Hours or Less $7.50
    - 4 - 24 Hours $9.75
  - Night and Weekend Rate Charges (Monday - Friday, 4:00 pm to 5:59 am, all day Saturday, Sunday)
    - 1 Hour or Less $2.00
    - 2 Hours or Less $3.00
    - 2 - 24 Hours $5.00

PITTSBURGH ATTRACTIONS & LANDMARKS

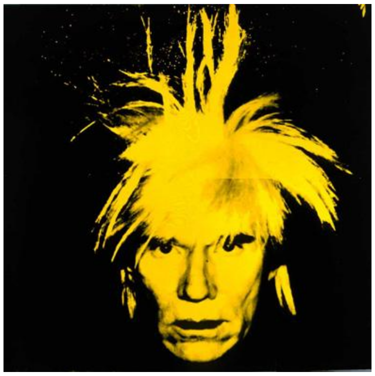
For those of you visiting Pittsburgh for the first time, you are in for a special treat. The city and the area around the Renaissance Hotel is plentifully endowed with landmarks and attractions that will appeal to people of all ages and interests. Within walking distance are historic sites, vista points, museums, science centers, performing arts centers, and top-notch restaurants, and that's just scratching the surface. The following pages provide a starting point; for more information please refer to

- http://www.visitpittsburgh.com
- http://pittsburgh.about.com/od/things_to_do/u/activities.htm
- http://pittsburgh.about.com/cs/kids/a/family_fun.htm

WITHIN WALKING DISTANCE

Carnegie Science Center	http://www.carnegiesciencecenter.org
	The most visited museum in Pittsburgh. **From Monday-Thursday, conference registrants can show their badge at the Science Center and receive free general admission for them and their families. This offer does not include parking or the Omnimax Theater, but does include the other exhibits such as the newly constructed Buhl Digital Dome, (which features the latest in projection), the Miniature Railroad & Village, and the USS *Requin*, a World War II submarine.**
Children's Museum of Pittsburgh	http://www.pittsburghkids.org
	Pittsburgh Children's Museum is a learning center featuring an array of interactive, kid-friendly exhibits, as well as temporary displays like Jump to Japan, and Earth-themed art works by Ned Kahn. Permanent displays include a simulated backyard with bubbling mud, an artist's studio, a replica of Mr. Rogers' television world, and much more. The museum resides north of the downtown area, near West Park (localguides.com).
Senator John Heinz History Center	http://www.pghhistory.org
	An affiliate of the Smithsonian Institution, and the largest history museum in Pennsylvania. The History Center is an educational center "that engages and inspires … with links to the past, understanding in the present, and guidance for the future by preserving regional history and presenting the American experience with a Western Pennsylvania connection." (wikipedia.org)

Andy Warhol Museum http://www.warhol.org



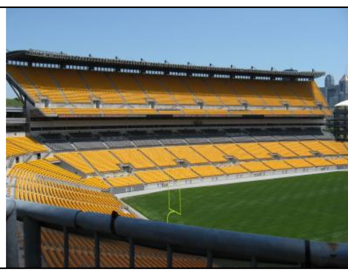
One of the most comprehensive single-artist museums in the world. Andy Warhol, the son of an immigrant Carpatho Rusyn laborer who came to work in Andrew Carnegie's steel mills, developed his skill as a young artist at the museum and library that Carnegie donated to the city. The museum collection includes more than 4,000 works of art by Warhol: paintings, drawings, prints, photographs, films and videos, and a collection of Warhol's "time-capsules" - boxed records of the artist's day-to-day dealings and penchant for collecting. While dedicated to Andy Warhol, the museum also hosts rotating exhibits by artists who push the boundaries of art, just as Warhol did.

Benedum Center for the Performing Arts http://www.benedumcenter.org

The Benedum Center is the home of the Pittsburgh Opera, Pittsburgh Ballet Theatre, and Pittsburgh Civic Light Opera.

"Into the Woods" will be performed on Sunday 9 August.

Heinz Field http://www.steelers.com



Home field for the Pittsburgh Steelers and University of Pittsburgh Panthers football teams.

The Steelers will host the Arizona Cardinals in a pre-season repeat of Super Bowl XLIII on Thursday evening, 13 August.

Heinz Hall for the Performing Arts http://www.pittsburghsymphony.org

Heinz Hall is the home of the Pittsburgh Symphony Orchestra (PSO) and the Pittsburgh Youth Symphony.

Unfortunately, there are no events scheduled at Heinz Hall during the week of the conference.

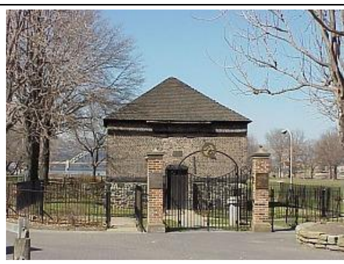
Station Square http://www.stationsquare.com

Station Square is an indoor and outdoor shopping area built at the location of a former station on the Pittsburgh and Lake Erie Railroad, with some of the original structures such as the freight house building and the elegant concourse being converted into restaurants and retail venues. Close to the dock for the Gateway Clipper Fleet of local river cruise boats and the Incline Railway.

Gateway Clipper Fleet http://www.gatewayclipper.com

The Gateway Clipper Fleet of riverboats tours the city from the perspective of the three rivers – the Ohio, Allegheny and Monongahela. Join in the fun aboard one of the sightseeing cruises, music and dance cruises, or a themed dinner cruise! There's something for everyone on one of the five historic ships! (discoveramerica.com). There are also Duck Boat Tours (see http://www.justduckytours.com).

Fort Pitt Blockhouse/Point State Park http://www.fortpittmuseum.com



Point State Park is a National Historic Landmark, and tells the story of Pittsburgh's pivotal involvement in the French and Indian War. The Fort Pitt Block House was constructed in 1764 and is the oldest building in Pittsburgh, as well as the oldest structure west of the Allegheny Mountains associated with colonial expansion. The Fort Pitt Museum preserves the frontier history of Pittsburgh and Western Pennsylvania through numerous exhibits and displays.

Mellon Arena http://www.mellonarena.com

Indoor stadium that primarily serves as the home of the Pittsburgh Penguins hockey team, as well as a facility for larger concerts.

Keith Urban will be performing on Thursday evening 13 August.

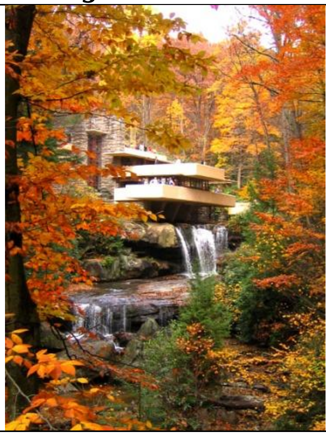
National Aviary http://www.aviary.org

America's largest aviary, the National Aviary is home to 600+ birds of more than 200 species, many of which are threatened or endangered in the wild. This is one of the most diverse collections in North America (wikipedia.org).

ATTRACTIONS THAT ARE A SHORT DRIVE AWAY

Kennywood Amusement Park http://www.kennywood.com

A National Historic Landmark known as the "roller coaster capital of the world" (New York Times); "six flags fun at two flags prices" (co-chair). Ride the Jack Rabbit and the Thunderbolt, both classic wooden coasters, or test your courage on the latest innovations in roller-coasters. There are many other rides that appeal to all ages.

Falling Water	http://www.fallingwater.org
	Fallingwater is a house designed by American architect Frank Lloyd Wright in 1935 in rural southwestern PA, 50 miles southeast of Pittsburgh. The house was built partly over a waterfall in the Laurel Highlands of the Allegheny Mountains. Hailed by TIME magazine shortly after its completion as Wright's "most beautiful job," the home partly inspired Ayn Rand's novel The Fountainhead, and is listed among Smithsonian magazine's Life List of 28 places "to visit before ...it's too late." Fallingwater was featured in Bob Vila's A&E Network production, Guide to Historic Homes of America. It was designated a National Historic Landmark in 1966. (wikipedia.org)
_Phipps Conservatory	http://phipps.conservatory.org/
	The gardens were founded in 1893 by steel and real-estate magnate Henry Phipps as a gift to the City of Pittsburgh. Its purpose is to educate and entertain people with formal gardens and various species of exotic plants. The facilities house elaborate gardens within the conservatory itself and on the adjoining grounds. In addition to its flora exhibits, the sophisticated glass and metalwork of the Lord & Burnham conservatory offers an interesting example of Victorian greenhouse architecture. (wikipedia.org)
_Pittsburgh Zoo and Aquarium	http://www.pittsburghzoo.org
	The Pittsburgh Zoo & PPG Aquarium is one of only six major zoo and aquarium combinations in the country. Also ranked among the top three children's zoos in the country, the Pittsburgh Zoo has thousands of animals in naturalistic habitats, a wonderful Kids Kingdom and a stunning indoor aquarium. Actively involved in wildlife conservation and species survival, the Pittsburgh Zoo also exhibits threatened or endangered species. (pittsburgh.about.com)
_Frick Art and Historical Center	http://www.frickart.org
	A cluster of museums and historical buildings focused on the interpretation of the life and times of Henry Clay Frick, industrialist and art collector.
Allegheny Observatory	http://www.pitt.edu/~aobsvtry
	An astronomical research institution, part of the Department of Physics and Astronomy at the University of Pittsburgh. The facility is listed on the National Register of Historical Places.

RESTAURANTS & LOUNGES

WITHIN HOTEL

Opus

- Pittsburgh's Opus Restaurant offers an American Infusion menu for breakfast, lunch and dinner, with a la carte service, Sunday breakfast buffet, salads and vegetarian entrees.

The Bridge Bar

- Open for lunch and dinner. A favorite meeting spot for hotel guests of the Renaissance, The Bridge Bar features a contemporary atmosphere and a delightful lunch or dinner menu. Enjoy your favorite cocktail and relax in this downtown Pittsburgh restaurant.

The Martini Bar (in lobby)

- Open for dinner. Enjoy a martini of your choice.

WITHIN WALKING DISTANCE

Bravo Franco

- 412-642-6677 ~ 613 Penn Avenue ~ http://bravofranco.com (Left out of the hotel, turn left at Penn Avenue. Bravo Franco is on the left about a half block down Penn Avenue.)
- Finest Italian cuisine in the heart of the Cultural District. The dining room is subdued, with a good-sized bar, and large connected dining areas. Large, comfortable chairs surround tables spaced so normal conversation is possible without raising one's voice.

Café Zao

- 412-325-7007 ~ 649 Penn Avenue ~ http://cafezao.com (Left out of the hotel, turn left at Penn Avenue, near the corner of 7th and Penn Avenue.)
- Latest restaurant from acclaimed Pittsburgh *Chef of the Year* Toni Pais, featuring Portuguese cross-cultural cuisine. Toni, a Portugal native, has owned the upscale, highly acclaimed Baum Vivant and the less-formal Café Zihno ("small café") in Shadyside. Café Zao ("big café") is within the Theater Square complex of the Cultural District.

Capital Grille

- 301 Fifth Avenue ~ 412-862-7537 Contact – Megan Gilson ~ http://capitalgrille.com
- A magnificent location for a more memorable dining experience. Right on 5th Avenue in the heart of the Golden Triangle. Discover dry-aged steaks just blocks from Heinz Field, picturesque desserts a few strokes from the Andy Warhol Museum, and more than 5,000 bottles of exceptional wine nestled near the banks of the Three Rivers.

Hyde Park

- 412-222-4014 ~ 247 North Shore Drive ~ http://www.hydeparkrestaurants.com Contact - Christine Zimmick
- A high end steakhouse located directly across the 6th Street Bridge, between PNC Park and Heinz Stadium. It is a 15 minute walk or 5 minute car ride away.

McCormick & Schmick's

- 412-201-6992 ~ 301 Fifth Avenue ~ http://www.mccormickandschmicks.com
- Fresh, Chef-crafted Seafood….excellent menu selection.

Morton's, The Steakhouse

- 412-261-7141 ~ 625 Liberty Avenue ~ http://www.mortons.com (Left out of the hotel, follow 6th Street, turn left at Liberty Avenue. Morton's will be on the left)
- Morton's, The Steakhouse, the nation's premier steakhouse group, specializes in classic, hearty fare, serving generous portions of USDA prime aged beef, as well as fresh fish, lobster and chicken entrees. Morton's is famous for its animated signature tableside menu presentation: steaks, whole Maine lobsters and other main course selections, along with fresh vegetables, are presented on a cart rolled to your table, where the server displays and describes each menu item in appetizing and entertaining detail.

The Original Fish Market

- 412- 227.3657 ~ 1001 Liberty Avenue ~ http://www.originalfishmarketpgh.com (Left out of the hotel, follow 6th Street to Liberty Avenue, go left, proceed to 10th Street. You will see the Westin Convention Center Hotel (the restaurant is adjacent to the hotel)).
- With an impeccable selection of the freshest seafood and shellfish flown in twice daily, a top rated sushi bar, and over 50 wines served by the glass, the Original Fish Market is truly a unique and upscale dining experience. Their menu changes frequently based on seasonal and market selections, and their educated, knowledgeable staff can aid you in selecting a meal to delight your palate and soothe your seafood soul.

Palate

- 412-434-1422 ~ 212 6th Street ~ http://www.palatebistro.com (Left out of the hotel, cross Penn Avenue, cross 6th Street, proceed down 6th. Palate will be on your right, directly across from Heinz Hall.)
- French fusion in the Cultural District. Executive Chef Ryan Racicot and proprietor John Valentine have created a modern bistro with nuances of classic French cuisine and a contemporary flair for spontaneous consumption. Palate is a crossroads of tastes and traditions. A place of casual elegance and eclectic energy.

Palomino

- 412-642-7711 ~ Four Gateway Center, Suite 100 ~ http://www.palomino.com (Left out of the hotel and proceed down 6th Street, cross Liberty Avenue and go right, down to Stanwix Street (at this point, Gateway Center will be directly in front of you). Cross Stanwix Street on the Liberty Avenue side of Gateway Center. Proceed down the sidewalk; entrance to Palomino on the left.)
- Palomino is a vibrant restaurant, bar and rotisserie famous for its style, hardwood fired Mediterranean cooking and versatile, imaginative menu. Guests appreciate Palomino's gracious hospitality and talented staff for their unsurpassed enthusiasm, friendliness and skill. Palomino offers an experience that makes guests feel great at a pleasing value.

Six Penn Kitchen

- 412-566-7366 ~ 146 6th Street ~ http://www.sixpennkitchen.com (Left out of the hotel, cross 6th at Penn Avenue and Six Penn Kitchen is at the corner, across from Starbucks).
- Six Penn Kitchen was designed to bring a new dining experience to the city of Pittsburgh. The goal was to create a neighborhood American bistro that focuses on relaxed but attentive service, unfussy but expertly prepared food at down to earth prices, and an overall feeling of hospitality that will cultivate a loyal fan base of guests who drop in for

lunch or dinner, weekly or monthly. Six Penn Kitchen was conceived by utilizing the talent and knowledge of local restaurateurs, in addition to relying on the resources of some folks behind the success of some of the best and most respected restaurants around the country. Six Penn Kitchen is a neighborhood restaurant with world class aspirations. By paying attention to the basics – true hospitality, great food, casually sophisticated environment – Six Penn Kitchen raises the bar on the art of dining casually.

Sonoma Grille

- 412-697-1336 ~ 947 Penn Avenue ~ http://www.thesonomagrille.com (Left out of the hotel, turn left at Penn Avenue, will be found between 9th and 10th Streets)
- Sonoma Grille is a restaurant that is eclectic yet approachable, where food and wine are uniquely prepared side by side. Their motto says it all, "A Meal Without Wine Is Like A Day Without Sunshine".

Tambellini's Ristorante

- 412-391-1091 ~ 139 7th Street ~ http://www.eatzucchini.com (Left out of the hotel, turn left at Penn Avenue, make left on 7th Street and you're there).
- Established 50 years ago, F. Tambellini's is Pittsburgh's finest Italian restaurant and a Pittsburgh tradition. Tambellini's 7th Street serves some of the finest fresh prepared fish in the city. The choices include lemon sole, sea scallops, Cod, in addition to specialty fish such as salmon, swordfish, and tuna. The sauces are home-made. Everything from the meat, marinara, clam sauce, and tomato basil are made daily. The meats are as fresh and tender as the best steak houses in Pittsburgh. They include items as sautéed veal, strip steak, filet mignon, and boneless chicken breast. Tambellini's 7th Street's cooking style stems from the Tuscan hills near Lucca, Italy- renowned for the finest olive oil and superb wines- the Lucchese kitchen is healthy, home cooking. Buon Appetito!

KID-FRIENDLY DINING

Atria's

- http://www.atrias.com ~ At PNC Park, just across the Clemente Bridge from the hotel.

Max and Erma's

- http://www.maxandermas.com ~ On Stanwix Street, one block from the hotel.

Palomino

- See above listing ~ suitable for older kids.

Primanti Brothers – Market Square

- http://www.primantibros.com ~ Unique sandwiches and a Pittsburgh tradition.

Station Square

- http://www.stationsquare.com/info/restaurants.cfm
- Many options, including Buca di Beppo, Hard Rock Café, Joe's Crab Shack, etc.

LOCAL MARKET

Rosebud Fine Food Market and Deli (corner of 7th Avenue and Fort Duquesne Boulevard)

Additional Information

Technical Sessions

This conference presents over 140 professional papers on space-flight mechanics, astrodynamics, and related topics, during 20 sessions. Three sessions run in parallel each morning and afternoon, excluding Tuesday morning. Morning sessions start at 8:00 am and end by 11:45 am. Afternoon sessions start at 1:30 pm and end by 5:15 pm except for Session 4 on Monday which ends at 5:40 pm. Sessions are held in the Symphony A, B, and C hotel meeting rooms facing the river (see the facilities floor plans).

Special Sessions

- The **Flight Dynamics for Magnetospheric Survey Missions** special session will be held Monday, 1:30 – 5:40 pm in the Symphony A room.
- The **Outer Planet Flagship Mission** special session will be held Tuesday, 8:00 – 11:45 am in the Symphony B room.

Speaker Orientation

On the day of their sessions, authors making presentations meet with their session chairs in the Jimmy Stewart room at 7:00 am each morning. A continental breakfast will be served. Speaker attendance is mandatory.

Volunteers

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

Presentations

Each presentation is limited to 20 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 microphone, 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.

Preprinted Manuscripts

Physical copies of preprinted manuscripts are no longer available or required for the Space Flight Mechanics Meetings or the Astrodynamic Specialist Conferences. Electronic preprints are available for download at least 72 hours before the conference at https://events.pxi.com/aas/reg/ for registrants who use the online registration system. The hotel provides conference guests with free 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 registrants will receive a CD of the proceedings mailed to them after 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 even if they delay their order until after the conference. Cost of Proceedings:

- Conference Rate **$240**
- Post-Conference Rate **$520** (approx.)
- Authors (post-conference) **$260** (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 Guidance, Control and Dynamics
Editor-in-Chief: George T. Schmidt, Massachusetts Institute of Technology
Manuscripts can be submitted via: http://www.writetrack.net/aiaa/

Journal of Spacecraft and Rockets
Editor-in-Chief: E. Vincent Zoby, NASA Langley Research Center
Manuscripts can be submitted via: http://www.writetrack.net/aiaa/

Journal of the Astronautical Sciences
Editor-in-Chief: Kathleen C. Howell
School of Aeronautics and Astronautics
1282 Grissom Hall
Purdue University
West Lafayette, IN 47907
(765) 494-5786
howell@ecn.purdue.edu

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 included in this program to the registration table before departing from the conference.

Committee Meetings

Committee seating is limited to committee members and invited guests. Committee meetings will be held according to the following schedule in the Jimmy Stewart room:

Joint AAS/AIAA TCs, Monday, 10 August, Noon – 1:30 pm.
AAS Space Flight Mechanics, Tuesday, 11 August, Noon – 1:30 pm.
AIAA Astrodynamics TC, Wednesday, 12 August, Noon – 1:30 pm.

Subcommittee Meetings

Conference Administration Subcommittee - Monday, Symphony B 5:45-6:45pm
Technical Administration Subcommittee - Monday, Symphony C 5:45-6:45pm
Website Administration Subcommittee - Tuesday, Symphony C 5-6pm

Session 1: Orbit Determination

Chair: Dr. Thomas Eller, Astro USA, LLC

08:00 **AAS 09 - 301** **Improved Radar Cross-Section "Target-Typing" for Spacecraft**
M.D. Hejduk, SRA International

With radar cross-section (RCS) data now acquiring uses in astrodynamic functions such as object correlation, proper characterization of the PDF of object RCS histories is gaining importance. Most space applications have used the Swerling chi-squared PDF"target types" proposed in 1954 for aircraft tracking, even though Swerling himself later repudiated his models and called for a broader investigation. The current study investigates six months of satellite radar tracking data (100M hits on over 10,000 objects) to reassess the Swerling models and investigate alternatives, specifically whether the promising lognormal distribution family can replace the chi-squared models and greatly simplify parameter estimation.

08:25 **AAS 09 - 302** **Satellite Collision Detection And Avoidance Using Star Trackers**
Reza Raymond Karimi, Troy A. Henderson, and Daniele Mortari, Texas A&M University

A novel method of collision detection and avoidance is presented based on on-orbit orbit determination. A star tracker on-board a satellite with known orbit parameters is used to determine the orbit of an unknown object. The orbit determination method is based on multiple line-of-sight measurements only. The object is then tracked to predict the time and location of a potential collision. The effects of measurement error and propagation error are discussed. Multiple orbit types are tested and the results presented, along with an analysis of the required number of observations and time between observations for accurate results.

08:50 **AAS 09 - 303** **Initial Orbit Determination From Ground Track Points**
Ossama Abdelkhalik and Ahmed Gad, Michigan Technological University.

Motivated by the need for algorithms for optimal orbit design for remote sensing space missions, the problem of orbit determination given three ground sites on the ground track is addressed. The problem is formulated and two solution algorithms are developed: the first algorithm finds the exact orbit whose ground track passes through the given ground sites. The second algorithm is more simple, yet calculates an approximate solution. The approximate algorithm can be used to get an initial guess for the solution, which can be used by the first algorithm for effective search for the exact solution.

09:15 **AAS 09 - 304** **Covariance Realism**
David A. Vallado, Center for Space Standards and Innovation; John H. Seago, Analytical Graphics, Inc.

Covariance information from orbit determination is becoming a popular means to assess the validity of many space operations. There have been scattered claims and discussion of realistic covariance, but few, if any, detailed studies to demonstrate the actual performance against independent references. This paper shows the performance of predicted ephemeris errors against reference and precision orbits to what the covariance propagation provides. Several satellite orbital classes are studied.

09:40 **Break**

10:05 AAS 09 - 305 Generalized Covariance Analysis of Additive Divided--Difference Sigma--Point Filters

J. Russell Carpenter, NASA Goddard Space Flight Center

The divided-difference sigma-point filter is a sequential estimator that replaces first-order truncations of Taylor series approximations with second-order numerical differencing equations to approximate nonlinear dynamics and measurement models. If theprocess and measurement noise enter the system additively, several simplifications are possible, including a substantial reduction in the number of sigma-points. As a consequence of the additive noise assumption, a generalized covariance analysis approach that partitions the contributions to the total error of a priori, process, and measurement noise may be applied to the additive divided-difference sigma-point filter. As an example, a simulated highly elliptical two-body orbit was estimated from biasedposition measurements. There is a significant nonlinearity at perigee, which occurs halfway through the simulation. The position biases are first-order Gauss-Markov processes.

10:30 AAS 09 - 306 CHANDRAYAAN-1 Accelerometer Based Real Time Orbit Determination

N.V.Vighnesam, Anatta Sonney, B.Subramanian, ISRO Satellite Centre, Bangalore, India

India's first moon mission Chandrayaan-I was launched on 22nd October 2008. The spacecraft was put into moon's polar, circular orbit by carrying out Earth and Lunar bound maneuvers. The thrust cut off/burn duration of Chandrayaan-I mission was controlledby accelerometers autonomously. A program named PROCAD (Precise Orbit Computation using Accelerometer Data) was developed to find the solutions to the orbit by making use of the accelerometer measurements from telemetry. This paper describes the methodology of orbit computation using accelerometer data in real-time. PROCAD orbit results were compared with operational orbit determination results during all phases of the mission.

10:55 AAS 09 - 307 Impact of Electric Propulsion Uncertainty On Orbit Prediction

Peter Zentgraf and Sven Erb, ESA/ESTEC

This paper analyses the achievable performance of the orbit prediction for a geostationary satellite using clusters of electrical propulsion (EP) thrusters for station-keeping and a star tracker based attitude control system. The challenge in the orbit prediction is that the real electrical propulsion thrust is known with limited accuracy only. In combination with thrust pointing errors, these inaccuracies can accumulate to large orbit position errors during long low thrust burn arcs. In the proposed paper the discrepancy between real and predicted satellite position will be determined in terms of probability and as a worst case scenario.

11:20 AAS 09 - 308 Orbit Determination of Chandrayaan-I using Lunar Laser Ranging Instrument (LLRI) Measurements

N.V.Vighnesam, Anatta Sonney, and N.S.Gopinath, ISRO Satellite Centre, Bangalore, India

India's first moon mission Chandrayaan-I carrying eleven scientific instruments was launched on 22nd October 2008. Lunar Laser Ranging Instrument (LLRI) is one of the scientific instruments carried by Chandrayaan-1. It is an instrument aimed to enhance the study of the moon's surface. The ISRO's mission operational orbit determination (OD) software was suitably updated to estimate the Chandrayaan-I orbit with LLRI measurements. This paper describes the method involved in observation modeling and OD results with simulated as well as live LLRI data of Chandrayaan-I. This work resulted in obtaining satisfactory results with LLRI measurements.

Session 2: Attitude Dynamics, Determination, and Control I

Chair: Dr. Sergei Tanygin, Analytical Graphics, Inc.

08:00 **AAS 09 - 309** **Constrained Time-Optimal Slewing Maneuvers for Rigid Spacecraft**
Robert G. Melton, Pennsylvania State University

Time-optimal slewing for orbiting astronomical observatories such as the Swift gamma-ray burst detector must include constraints to protect delicate optical sensors from accidental exposure to high-intensity sources such as the Sun, Earth and Moon. Thispaper considers the problem of slewing a spacecraft in minimum time in order to align an onboard telescope with a particular target, with one or more path-constraints that maintain a minimum angular distance between the optical sensor axis and the high-intensity sources. The problem is solved via a pseudospectral method, with solutions showing a relatively simple control-switching structure.

08:25 **AAS 09 - 310** **Approaches to Address Instability of the Inverse Model in Iterative Learning Control**
Yao Li and Richard Longman, Columbia University

Iterative learning control aims to achieving high precision tracking by learning from hardware experience performing a desired maneuver. Spacecraft applications relate to repeated scanning maneuvers. There is a fundamental difficulty that the inverse of adigital system is very often unstable, which makes finding the input needed to produce zero error into the solution of an unstable system. Previous work suggested avoiding this by asking for zero error every other step. This approach is examined in detail here, and it is shown that under certain conditions there can still be difficulties. Methods are suggested to address this new situation.

08:50 **AAS 09 - 311** **Dynamically Driven Helmholtz Cage for Experimental Magnetic Attitude Determination**
Andrew Klesh, Matt Bennett, Dylan Boone, Sheryl Seagraves, and James Cutler, University of Michigan

The Radio Aurora Explorer (RAX) is a small, NSF-sponsored spacecraft being designed, built, and tested by students at the University of Michigan for launch in December 2009. The RAX team has created a dynamically-controlled Helmholtz cage to characterizeand calibrate magnetic sensors while serving as an analog-orbit mission simulator. The Helmholtz cage is capable of automatically simulating entire orbits in real-time through the use of Satellite Tool Kit and MATLAB, enabling the team to validate its primary attitude sensor in the lab. This paper presents the design, construction, and capabilities of the RAX Helmholtz cage through experimental and operational results.

09:15 **AAS 09 - 312** **A Direct Method For Identifying Linear Time-Varying State-Space Models**
Minh Q. Phan, Dartmouth College; Richard W. Longman, Columbia University; Jer-Nan Juang. National Cheng-Kung University

This paper presents a direct method to identify time-varying state-space models from input-output data. Unlike previous indirect methods that either work through the observer Markov parameters or the canonical representations, this method computes the time-varying state-space matrices directly from input-output data in one linear step. The key is to use the input-output data directly to form the state variables from which the time-varying state-space models are derived. The paper also shows how to perform model reduction on the identified time-varying state-space models. Numerical examples are used to illustrate this direct time-varying state space model identification method.

09:40 **Break**

10:05 **AAS 09 - 313** **Comparison of State-of-The-Art Steering Logics for Control Moment Gyroscopes**

Frederick A. Leve and Norman G. Fitz-Coy, University of Florida; George A. Boyarko, Naval Postgraduate School

This paper discusses current state-of-the-art (SOA) of Generalized Inverse Steering Logic (GISL), Feedback Steering (FS), and the ahead singularity index methods available for singular avoidance/escape for attitude control systems of single-control momentgyroscopes (SGCMGs). A novel steering logic known as the Hybrid Steering Logic (HSL) will be introduced and compared with SOA methods. HSL's advantages lie for systems that require attitude tracking precision and have constraints on gimbal rates and accelerations. All steering logics will be validated by the following metrics: RMS torque error, RMS gimbal rates, maneuver completion time, and computational burden.

10:30 **AAS 09 - 314** **Adaptive Angular Velocity Estimator**

Bong Su Koh and Daniele Mortari, Texas A&M University

Quaternion describing pure-spinning rigid-body dynamics defines a 3-D hyperplane in a 4-D space. As long as the angular velocity does not change direction, the quaternion remains on that hyperplane. This paper shows how to identify this hyperplane and howto extract the angular velocity information from subsequent quaternions. Specifically, the direction of the angular velocity is derived from the instantaneous quaternion's plane of rotation while the modulus is derived from the angles between quaternions. Motivation comes from the possibility to use fast star trackers to estimate the angular velocity and/or to provide Kalman filters with good initial angular velocity estimates.

10:55 **AAS 09 - 315** **Adaptive Attitude Control of Spacecraft without Velocity Measurements Using Chebyshev Neural Network**

An-Min Zou and Krishna Dev Kumar, Ryerson University,

This paper proposes an adaptive neural controller for the attitude tracking control of a rigid spacecraft without angular velocity measurements and in the presence of an unknown mass moment of inertia matrix and external disturbances. The Modified Rodrigues parameters are employed for the representation of spacecraft attitude. The system uncertainty, which may include unknown mass moment of inertia matrix

and external disturbances, is estimated by introducing a Chebyshev neural network. The proposed controller is robust not only to structured uncertainty such as unknown mass moment of inertia matrix but also to understructured uncertainty such as external disturbances. Results of the numerical simulations state that the proposed controller is successfulin achieving high attitude performance in presence of system parameter uncertainties and external disturbances.

Session 3: Rendezvous, Relative Motion, and Proximity Missions

Chair: Dr. Aaron Trask, Apogee Integration

08:00 AAS 09 - 316 **Modeling and Optimization of a Spacecraft Maneuvering with Respect to a Tumbling Object**

George Boyarko, Oleg Yakimenko, and Marcello Romano, Naval Postgraduate School

This paper deals with the development algorithms allowing solving for the optimal close rendezvous problem of two spacecraft where one is freely tumbling. It first analyses the existing approaches that are limited to simplified models and control strategies. The three-dimensional twenty-state model of two-spacecraft rendezvous developed. Next, the optimal control problem is formulated and dealt with using indirect (Minimum Principle) and one of the direct (pseudospectral) methods. The costate equations are presented as well as the terminal variations. These conditions are used to verify the optimality of the solution obtained from the direct method.

08:25 AAS 09 - 317 **Optimal Control For Proximity Operations And Docking**

Daero Lee and Henry Pernicka, Missouri University of Science & Technology

This paper proposes optimal control techniques for determining translational and rotational maneuvers that facilitate proximity operations and docking. Two candidate controllers that provide translational motion are compared: A state-dependent Riccati equation controller is formulated from the nonlinear relative motion dynamics, and a linear quadratic tracking controller is formulated from the linearized relative motion. A linear quadratic Gaussian controller using star trackers to provide quaternion measurements is designed for precision attitude maneuvering. The attitude maneuvers are evaluated for different final axis alignment geometries depending on the approach distance. A six degree-of-freedom simulation demonstrates that the controllers perform proximity operations and docking successfully.

08:50 AAS 09 - 318 **A Model for J2-perturbed Linear Relative Motion about Mean Circular Orbits**

S. R. Vadali, Texas A&M University

A linear model for perturbed relative motion in the vicinity of a mean circular orbit has been developed. It accounts for the secular as well as short-period perturbation effects. The fidelity of the model has been verified on several test cases and by comparisons of the in-track errors with those associated with linearization of the two-body gravitational field. Results show that the primary source of error is due to linearization of the two-body gravitational field, the J2-approximation is a secondaryerror source.

09:15 AAS 09 - 319 **Guidance, Navigation And Control System For Proximity Operations And Docking**

Daero Lee and Henry Pernicka, Missouri University of Science & Technology

This study develops an integrated guidance, navigation and control system for proximity operations and docking of a spacecraft. The translational maneuvers are determined through the integration of the state-dependent Riccati equation control formulated by the nonlinear relative motion dynamics and the relative navigation using a Lidar and a vision sensor system, where a sensor mode change is done according to the approach distance in order to provide efficient navigation. The Clohessy-Wiltshire equationsare used to determine the proper transfer time, reference trajectory, required delta V. The attitude maneuvers, determined from a linear quadratic Gaussian-type control using star trackers, provide the precise attitude control and robustness to the uncertainty of the moment of inertia. A six-degree of freedom simulation demonstrates the effectiveness of the integrated system.

09:40 **Break**

10:05 **AAS 09 - 320** **A General Pose Estimation Algorithm For An Arbitrary Number Of Target Spacecraft Features**

Andrew F. Heaton and Richard Howard, NASA MSFC

Docking sensors are integral to space rendezvous. In the 2007 Orbital Express mission, a NASA sensor helped achieve five automated dockings using an iterative algorithm for pose estimation called Inverse Perspective. The Inverse Perspective algorithm requires three identified features on the target spacecraft for a 6-DOF pose estimate. In this paper, we present a method of incorporating a general number of spots into the solution. The "n-spot method" is tested for accuracy, robustness and convergenceusing simulated target positions and existing sensor test data. The 3-spot Inverse Perspective method is also compared to Finsterwalder's solution of the same problem.

10:30 **AAS 09 - 321** **Hypercomplex Eccentric Anomaly in the Unified Solution to the Relative Orbital Motion**

Daniel Condurache, Vladimir Martinusi, Technical University "Gheorghe Asachi" Iasi, Romania

The present work presents an approach to the relative orbital motion by using hypercomplex numbers. An extension to this notion is used for vectors, by introducing the hypercomplex vector in the same way as hypercomplex numbers are defined. The solution to the relative orbital motion is offered in all possible situations (it stands for any Keplerian reference or targeted trajectories). A unified view on the relative orbital motion is suggested, by generalizing the previous approaches. The solution is offered to the nonlinear model of the relative motion and it is expressed in a coordinate-free hypercomplex vectorial closed form. The key element of this approach is the hypercomplex eccentric anomaly, introduced via a Sundman-like vectorial regularization.

10:55 **AAS 09 - 322** **From Elliptic Restricted Three-Body Problem to Tschauner-Hempel Equations: A Control Strategy Based on Circular Problems**

Mai Bando and Akira Ichikawa, Kyoto University

Equations of motion of a satellite in the elliptic restricted three-body problem , with true anomaly as an independent variable , are derived, and a feedback control which steers the satellite to a halo orbit of the circular restricted three-body problemis proposed. Then reduction of equations of motion of the satellite with respect to the moon to those of the relative motion along an eccentric orbit is discussed. Finally, the formation and reconfiguration problem of the Tschauner-Hemel equations aresolved by the feedback control of the Hill-Clohessy-Wiltshire equations.

Session 4: Special Session: Flight Dynamics for Magnetospheric Survey Missions

Chair: Dr J. Russell Carpenter, NASA GSFC

13:30 **AAS 09 - 328** **Overview of the Magnetospheric MultiScale Formation Flying Mission**
Cheryl J. Gramling, NASA/Goddard Space Flight Center

The Magnetospheric MultiScale (MMS) Mission consists of four identical spinning spacecraft flying in tetrahedral formation in highly eccentric Earth orbits to study the phenomenon of collisionless magnetic reconnection and particle acceleration in the electron diffusion regions of the Earth's dayside magnetopause and nightside neutral sheet. The mission design involves a two-phase apogee approach where the apogee region of the orbit provides long durations in the areas of prime science interest. To analyze the phenomenon that occurs at different scales and speeds, the nominal side lengths of the tetrahedron, referred to as the separation, purposely vary from 400 km to 10 km. This paper discusses the science and engineering constraints on the mission, hence the rationale for the mission design and navigation system of MMS.

13:55 **AAS 09 - 323** **MMS Orbit Propagation Sensitivity to Navigation Errors**
J. Russell Carpenter, NASA Goddard Space Flight Center

The objective of this paper is to address the need for MMS onboard navigation solutions to propagate accurately. The onboard navigation function is not intended to perform state prediction; rather, it produces definitive states that ground operators willuse to generate flight dynamics and science products. Many of these products, such as maneuver plans, conjunction predictions, and tracking acquisition plans, require predictive states. We conclude that in order for definitive states to predict accurately, they must not only have good definitive accuracy, but must also limit the errors in semi-major axis, eccentricity, and inclination.

14:20 **AAS 09 - 325** **Magnetospheric Multiscale (Mms) Mission Commissioning Phase Orbit Determination Error Analysis**
Lauren Chung and Stefan Novak, a.i. solutions, Inc.

This paper summarizes the three-sigma error results from a linear covariance analysis to determine the type and amount of tracking data needed to plan a series of perigee raising maneuvers during the MMS commissioning phase. The accuracy achievable usingonly Deep Space Network (DSN) tracking data or both DSN and and Space Network (SN) tracking is studied. Sensitivities to the batch-least-squares orbit determination arc length; tracking density; tracking type; and variations in the estimated parameter set are also investigated. For each scenario, maximum, absolute and relative position and velocity errors were calculated and analyzed over the definitive and predictive timespans.

14:45 **AAS 09 - 324** **Magnetospheric Multiscale Mission (MMS) Phase 2b Navigation Performance**
Paige Thomas Scaperoth and Anne Long, a.i. solutions, Inc.; Russell Carpenter, NASA Goddard Space Flight Center

The Magnetospheric Multiscale (MMS) mission, which consists of four spacecraft flying in a tetrahedral formation, has challenging requirements associated with determining and maintaining the relative separations required to meet the science requirements.The baseline navigation concept for MMS is for each spacecraft to independently estimate its position, velocity and clock states using GPS pseudoranges. State estimation is performed onboard using the Goddard Enhanced Onboard Navigation System flight software, which is embedded in a Navigator receiver. This paper summarizes the results from high-fidelity simulations to determine if MMS navigation requirements can be met between and following the maintenance maneuver sequence.

15:10 **Break**

15:35 **AAS 09 - 327** **Launch Window Opportunity Assessment for the Magnetospheric Multi-Scale Mission**
Cheryl Gramling, NASA Goddard Space Flight Center; Laurie Mann and Jason Tichy, a.i. solutions, Inc.

The Magnetospheric Multi-Scale (MMS) Mission is a tetrahedral formation mission designed to study magnetic reconnection in the Earth's magnetosphere. To sample the regions of interest, the MMS mission will be divided in two main science phases: Phase 1 and Phase 2 with 1.2 Re × 12 Earth Radii (Re) and 1.2 Re × 25 Re orbits, respectively, which are initially inclined at 28.5 deg with respect to the Earth's equator. These highly eccentric orbits are designed to provide long time periods in the science region of interest, which is centered at apogee. This paper focuses on quantifying the MMS launch window opportunities defined by the associated science and operating parameters and constraints.

16:00 **AAS 09 - 326** **MMS Separation and Commissioning Phase Maneuvers**
Trevor Williams, NASA Goddard Space Flight Center

The four Magnetospheric MultiScale (MMS) spacecraft are launched in a stack, and released sequentially by identical sets of springs. They then enter a four-month commissioning phase, during which they must: raise the perigee of their highly elliptical orbits from the initial altitude of 185 km, to avoid any possibility of subsequent imminent deorbit from lunisolar perturbations; deploy wire booms and other appendages; calibrate experiments, thrusters and navigation systems; and enter into the initial tetrahedron formation for science observations around apogee. This paper will discuss the design of the various maneuvers required during the commissioning phase, starting with the separation maneuvers.

16:25 **AAS 09 - 330** **Optimal Control and Near Optimal Guidance for the Magnetospheric MultiScale Mission (MMS)**
Steven P. Hughes and Edwin Dove, NASA Goddard Space Flight Center

In this work, we present an approach to minimize the fuel required to recon gure a formation while simultaneously satisfying near-optimal guidance conditions as determined by the MMS science-based metric. Our approach employs Nonlinear Programming (NLP) where the cost function is the total delta-v expended by all spacecraft during a particular maneuver sequence. Previous work has shown that there are many classes of formations with similar values for the science-based metric, but with different relative geometries. We formulate the problem to select a minimum fuel solution from the set of near-optimal formations. Numerous nonlinear constraints are applied to ensure that the resulting formations meet mission requirements. These constraints include periodicity conditions, maneuver location constraints, close approach constraints, and delta-v equalization constraints among others.

16:50 **AAS 09 - 329** **Apogee Raising for the Magnetospheric MultiScale Formation Flying Mission**
Cheryl Gramling, NASA Goddard Space Flight Center; Craig Roberts, Jason Tichy, and Michael Volle, a.i. solutions, Inc.

The Magnetospheric MultiScale (MMS) Mission consists of four identical spacecraft flying in formation in highly eccentric Earth orbits. The mission requires an increase in the apoapsis radius from 12 Re to 25 Re with the return of all 4 spacecraft to a loose formation at apogee, where a tetrahedral formation can be reestablished for the beginning of the final science campaign. The apogee raising technique used to meet operational and science constraints is described in this paper along with failure recovery scenarios.

17:15 **AAS 09 - 331** **Conjunction Assessment Analysis for the magnetosphere Multi-scale (MMS) Formation**

David McKinley and David Rohrbaugh, a.i. solutions, Inc.; Russell Carpenter, NASA GSFC

The highly elliptical orbit of the MMS formation-flying mission presents a unique conjunction assessment environment. The MMS spacecraft will spend part of its highly elliptical orbit in a debris-free environment at apogee while transitioning through densely populated regions such as the geo belt and LEO at perigee. An analysis was performed to characterize the debris environment that MMS will encounter and estimate the number of Risk Mitigation Maneuvers (RMM) that could potentially be required. Additionally, an assessment of the GSFC Conjunction Assessment (CA) tool suite was performed to determine its applicability for performing conjunction assessment for the MMS mission.

Session 5: Trajectory Optimization I

Chair: Jon Sims, Jet Propulsion Laboratory

13:30 **AAS 09 - 332** **A Comparison of Pseudospectral Methods Using Gaussian Quadrature Nodes for the Solution of Optimal Control Problems**
Divya Garg and Michael Patterson, University of Florida; David A. Benson, Draper Laboratory, Cambridge, MA; Geoffrey T. Huntington, Blue Origin, LLC; William Hager and Anil V. Rao, University of Florida

A comparison is made between three different pseudospectral methods for solving optimal control problems using collocation at Gaussian quadrature nodes. In partcular, the fundamental mathematical properties of these three different collocation schemes are developed. Two examples are studied to show the differences between the various schemes.

13:55 **AAS 09 - 333** **A Learning Approach to Sampling Optimization Applied to a Global Trajectory Optimization Problem**
Troy A. Henderson and Daniele Mortari, Texas A&M University

A method of optimization based on rejection sampling (called the Learning Approach to Sampling Optimization) is presented for solving a global trajectory optimization problem. The given trajectory optimization problem was posed by ESA/ACT and has known solutions. The Learning Approach algorithm will be applied to the problem and the results are compared with the known solutions.

14:20 **AAS 09 - 334** **A Survey of Numerical Methods for Trajectory Optmization**
Anil V. Rao, University of Florida

A survey of numerical methods for trajectory optimization is given. The general trajectory optimization problem is posed and the two broad classes of indirect and direct methods for solving trajectory optimization problems are discussed. A brief discussion is then given of well known software tools to solve trajectory optimization problems.

14:45 **AAS 09 - 335** **Method and Solution for the 2009 Global Trajectory Optimization Contest**
Brianna Aubin, Bruce Conway, Jacob Englander, Alexander Ghosh, Chris Martin, University of Illinois at Urbana-Champaign; Bradley Wall, Embry-Riddle Aeronautical University at Prescott AZ

The 2009 Global Trajectory Optimization Contest challenged participants to design a trajectory leaving from the Earth and traveling to rendezvous with one near-earth asteroid in a time frame of ten years, while intercepting as many asteroids as possible along the way. The dual objective of maximizing the final mass of the spacecraft was used as a tiebreaker. In the solution presented here, a heuristic spiral method was used to generate a sequence of asteroids, and a direct transcription method was used tomaximize the spacecraft mass. A sequence of 21 asteroids was found, with a final spacecraft mass of 524kg.

15:10 **Break**

15:35 **AAS 09 - 337** **Fast Sensitivity Computations for Trajectory Optimization**

Nitin Arora, Ryan P. Russell, and Richard W. Vuduc, Georgia Institute of Technology

Gradient based trajectory optimization relies on accurate sensitivity information to robustly move a solution towards an optimum. Computational complexity of sensitivity calculations increases exponentially for higher problem dimensions and orders. Hence, the computation of these sensitivities is traditionally a major speed bottleneck in trajectory optimization algorithms. We propose to use Nvidia's GPU (Graphics processing unit) to rapidly calculate the derivatives in a multilayer parallel approach while the CPU (central processing unit) sequentially computes the less expensive state equations. Typical multi-body (e.g Earth-Moon-Sun plus oblatness) propagations are used to compare performance with mainstream methods for obtaining sensitivities

16:00 **AAS 09 - 338** **New Approach to NLP-Based Trajectory Optimization of Space Applications**

Sven O. Erb, European Space Agency; Andreas Wiegand, ASTOS Solutions

This paper presents a novel approach to NLP-based trajectory optimization through a dedicated NLP solver development that is geared towards industrial space applications. eNLP was developed as an all-modular solver that can be used as an IP-method with filters, or as an SQP-method with several solution schemes for the QP subproblem. An all novel capability is the reverse communication feature for online user intervention. The paper will present the concept behind eNLP for space applications and dedicatedtuning of the optimization settings. Further, results will be shown for application-driven trajectory optimization problems related to multi-stage small launcher trajectory optimization, optimum low-thrust satellite transfers and reentry trajectory optimization with complex entry interface.

16:25 **AAS 09 - 339** **On Ballistic Acquisition of Short Period Out-Of-Ecliptic Trajectories**

Jun’ichiro Kawaguchi, Yasuhiro Kawakatsu, Mutsuko Morimoto, Japan Aerospace Exploration Agency (JAXA); Justin A. Atchison, Cornell University

This paper presents new orbital synthesis results to achieve short period out-of-ecliptic trajectories in ballistic way, instead of electric propulsion or solar sail acceleration. The strategy developed utilizes a Jovian gravity assist first, followed bypolar very high speed gravity assists by Earth or Venus. So far, the use of very high speed gravity assists has been conceived not practical. However, this paper presents those still effectively contribute to amending the trajectories periods, and to acquiring small sized out-of-ecliptic trajectories. The biggest advantage here is to reduce propellant mass drastically and is to enable large spacecraft placed on such orbit.

Session 6: Orbital Dynamics I

Chair: Dr. Matthew Berry, Analytical Graphics, inc

13:30 **AAS 09 - 340** **Analytic Corrections For Periodic Orbits In The Three Body Problem With Small Mass Parameter**
Mohammed Ghazy and Brett Newman, Old Dominion University

In this paper, an approximate solution to the circular restricted three body problem, when the mass parameter is small and motion of third body is in the vicinity of the first primary, is subject to an analytic iterative correction process. The iterativescheme is based on adding small terms with order of magnitudes less than the base solution. These terms are obtained through solving differential equations with periodic coefficients using Floquet theory and a perturbation technique. The out of plane motion is found to be decoupled from the in plane motion and only exist under out of plane initial conditions excitation.

13:55 **AAS 09 - 341** **Improving Access to the Semi-Analytical Satellite Theory**
Paul Cefola, Consultant in Aerospace Systems, Spaceflight Mechanics, & Astrodynamics; Zach Folcik, MIT LL; Ken Kim and Don Phillion, Lawrence Livermore National Lab

The semi-analytical theory for the motion of a space object replaces the conventional equations of motion with two formulas: (1) equations of motion for the mean elements, and (2) expressions for the short periodic motion. The semi-analytical satellitetheory software exists in two forms: as an option within the GTDS orbit determination system and as the Standalone Orbit Propagator Package. Both GTDS and the Standalone have been ported to the Linux environment. The current paper describes comparisontests between the Linux GTDS DSST and the Linux DSST Standalone. A plan for a satellite theory distribution package is discussed.

14:20 **AAS 09 - 342** **Constraints on the Motion of Electrostatically Charged Spacecraft**
Joseph Gangestad, George Pollock, and James Longuski, Purdue University

Active modulation of the surface charge of a Lorentz spacecraft enables many capabilities–including inclination change, J2 mitigation, and planetary escape–without propellant cost. We develop Lagrange's planetary equations with the Lorentz force and use these analytical expressions to explore the dynamics. Behavior discovered empirically in earlier studies follows directly from the planetary equations. The small tilt of a magnetic dipole has a negligible effect on the orbit, and J2 can be leveraged to manipulate orbital elements. We have also found a single expression that constrains the reachable set of orbits for propellantless planetary escape and capture.

14:45 **AAS 09 - 343** **Rock-Around Orbits**
Scott Bourgeois and Dr. Daniele Mortari, Texas A&M University

The ability to observe resident space objects (RSOs) is a necessary requirement for space situational awareness. Using a satellite with a specific orbit relative to an RSO’s orbit, one can create an orbit that will surround the reference orbit allowing the satellite in the Rock-Around-Orbit orbit to have a 360 degree view of any RSOs in the reference orbit over a given period of time.

15:10 **Break**

15:35 **AAS 09 - 344** **Keeping A Spacecraft On A Circular Orbit Around An Earth Moon Lagrange Point**

Mohammed Ghazy and Brett Newman, Old Dominion University

A station keeping strategy for a spacecraft orbiting a collinear equilibrium point in the Earth-Moon system is introduced. A nominal circular solution which is derived from the Jacobi integral equation, employing elliptic integral theory, is used in a plane perpendicular to the line joining the two primaries. Thrust control inputs, which are found to be nonlinear functions of time, are used to negate the instability of the nominal orbit. When transforming into a cylindrical coordinate system only two components of thrust are required. Orbit parameters are chosen so that total velocity increment required in each period is minimized.

16:00 **AAS 09 - 345** **Orbital Maneuvering with a Solar Sail through the Use of Natural Attitude Coning**

Jay W. McMahon and Dale A. Lawrence, University of Colorado at Boulder

It has been shown that attitude equilibria exist in the LVLH frame for a solar sail under the influence of gravity gradient, aerodynamic, and solar torques. This paper explores the orbital effects of solar sails at and around these equilibria. It is shownthat by moving the attitude in coning motions about the stable equilibria at orbital rates, nearly any orbital effect can be induced. Scaled results that can be easily applied to different sails or orbital conditions are derived. One possible applicationof modifying and/or stabilizing Sun-synchronous orbits is discussed in detail.

16:25 **AAS 09 - 346** **A New Navigation Force Model for Solar Radiation Pressure**

Jay W. McMahon and Daniel J. Scheeres, University of Colorado

This paper presents a new force model for solar radiation pressure acting on a satellite. The new model is based on a Fourier series representation of the satellite properties based on the position of the Sun with respect to the body. The perturbative effects on the satellite's orbit due to the solar radiation pressure are derived. This preliminary study shows that for a spacecraft in a circular orbit with synchronous rotation, the secular effect of solar radiation can be described with only seven Fouriercoefficients. An example is discussed based on the GRACE satellite.

16:50 **AAS 09 - 347** **Solar Radiation Pressure Perturbations at Binary Asteroid Systems**

Julie Bellerose and Hajime Yano, JAXA/JSPEC; Daniel J. Scheeres, University of Colorado

Missions to binary asteroid systems have been seriously considered in the past decade. There are still uncertainties regarding the effects of solar radiation pressure on both in plane and out-of-plane dynamics. In this paper, we use a simple ellipsoid-sphere model to provide a general characterization of the solar radiation pressure, and we investigate the effects of a binary system free parameters, and the planes of orbits. We provide case studies of targets of interest such as (65803) Didymos and 1999 KW4, and we compare to cases of single asteroids.

Session 7: Planetary, Asteroid, and Deep Space Missions I

Chair: Angela Bowes, NASA LaRC / Analytical Mechanics Associates

08:25 **AAS 09 - 348** **Accessing the Design Space for Solar Sails in the Earth--Moon System**
Kathleen Howell and Geoffrey G. Wawrzyniak, Purdue University

Using a solar sail, a spacecraft orbit can be offset from a central body. Such a trajectory is desirable for a single-spacecraft relay to support communications with an outpost at the lunar south pole. Although trajectory design within the context of theEarth-Moon restricted problem is advantageous, it is difficult to envision the design space for offset orbits. Numerical techniques to solve boundary-value problems can be employed. Finite-difference methods possess lower accuracy, but are simple to understand and implement. A survey of different sail characteristics and initial guess strategies for offset orbits illuminates the available design space to the analyst.

08:50 **AAS 09 - 349** **Cassini-Huygens Maneuver Experience: First Year of the Equinox Mission**
Emily M. Gist, Christopher G. Ballard, Troy D. Goodson, Yungsun Hahn, Paul W. Stumpf, Sean V. Wagner, and Powtawche N. Williams, Jet Propulsion Laboratory

The Cassini-Huygens spacecraft was launched in 1997 on a mission to observe Saturn and its many moons. After a seven-year cruise, it entered a Saturnian orbit for a four-year, prime mission. Due to the success of the prime mission, spacecraft health and remaining propellant, a two-year extended mission, the Equinox Mission, was approved. Maneuver designs and analyses performed through the first year of the Equinox Mission are presented. Results for the 43 most recent maneuvers are given. A substantial contribution to the navigation success of the Cassini-Huygens spacecraft is the continued accurate performance, exceeding the pre-launch expectations and requirements.

09:15 **AAS 09 - 350** **Flight Dynamics Operations for the IBEX Mission: The First Six Months**
Lisa Policastri, John Carrico, Timothy Craychee, and Ryan Lebois, Applied Defense Solutions; Mike Loucks, Space Exploration Engineering

At the time of this presentation, the Interstellar Boundary Explorer (IBEX) will have completed its minimum six-month mission. This paper gives details of the flight dynamics operations for this first six months. The authors describe the specifics of how orbit determination is performed for this eight-day period cislunar trajectory with a 0.9 eccentricity. The methods used to calculate the orbit covariance, including predicted maneuvers, are described, as well as comparisons of the predictions versus the post-fit solutions. The techniques used to handle the high eccentricity orbit are also described.

09:40 **Break**

10:05 AAS 09 - 351 Overview of the Cassini Solstice Mission Trajectory
John Smith and Brent Buffington, Jet Propulsion Laboratory

The Cassini Project has completed a 7.2 year mission extension (1-Jul-2010 to 15-Sep-2017) which will govern the remainder of Cassini’s operational lifetime. The resultant extended mission, stemming from 1.5 years of development, includes an additional 54close Titan flybys, 12 close Enceladus flybys, 11 close flybys of other moons, and 160 orbits about Saturn in a variety of orientations. The mission ends with a spectacular series of orbits whose periapses are only a few thousand kilometers above Saturn’s cloud tops culminating with impact into Saturn. This paper describes the different phases of the Solstice mission and the associated design methodology.

10:30 AAS 09 - 352 Constraints for Mars Round Trips Mission Design.
Nicola Sarzi Amade' and James R. Wertz, Microcosm, Inc.

This paper presents the basic constraints for interplanetary round trip travel, in the general case of orbits with non-zero eccentricity and non-zero inclination. A more specific study of the possible options for round trip travels to Mars is presented. Options at high energy and intermediate energy are discussed as well. Given a transfer time and a transfer arc, it is possible to determine the required arrival times. An “interplanetary train schedule” of transfer times to Mars can be constructed as a function of the delta-V. The behavior of the constraints near transfer time singularities, and the impact of orbit element variation are presented. Costs and masses required for human missions are estimated.

Session 8: Special Session: Outer Planet Flagship Mission

Chair: Nathan Strange, NASA / JPL

08:00 **AAS 09 - 354** **Mission Design for the Jupiter Europa Orbiter Flagship Mission Study**
Anastassios Petropoulos and Damon Landau, Jet Propulsion Laboratory; Kevin Kloster, Purdue University

With high priority given to exploration of Europa in the National Research Council's last Planetary Science Decadal Survey, NASA commissioned the development of a mission concept for a flagship-class mission to Europa, which would include international collaboration, especially with an ESA Jupiter Ganymede Orbiter mission. Here we describe the Jupiter Europa Orbiter mission design. Numerous types of gravity-assist trajectories to Jupiter are analysed, including a nominal 2020-launch, Venus-Earth-Earth trajectory. We also present a nominal Jovian system tour, whose purpose is not only study of the system, but also reduction of the size of the insertion burn into Europan orbit.

08:25 **AAS 09 - 357** **An Overview of the Jupiter Europa Orbiter's Europa Science Phase Orbit Design**
Robert E. Lock, Jan M. Ludwinski, Anastassios E. Petropoulos, Karla B. Clark, and Robert T. Pappalardo, Jet Propulsion Laboratory

Jupiter Europa Orbiter (JEO), the NASA element of the joint NASA-ESA Europa Jupiter System Mission (EJSM), would launch in February 2020 and arrive at Jupiter in December of 2025. In the baseline concept, JEO would perform a multi-year study of Europa and the Jupiter system, including 30 months of Jupiter system science and a comprehensive Europa orbit phase of 9 months. This paper will provide an overview of the JEO mission and describe the Europa Science phase orbit design and the related science priorities, model payload and operations scenarios needed to conduct the Europa Science phase as currently envisioned.

08:50 **AAS 09 - 353** **Europa Orbiter Mission Design With Io Gravity Assists**
Kevin W. Kloster and James Longuski, Purdue University; Anastassios E. Petropoulos, Jet Propulsion Laboratory

Recent improvements in radiation hardening enable spacecraft to endure greater radiation exposure than previously possible, in particular allowing the current iteration of the Europa Orbiter mission to perform several consecutive flybys of Io. The strategy for designing tours with Io flybys differs significantly from schemes developed for previous versions of the mission, but the Tisserand graph continues to provide important insights into the tour design. While Io flybys increase the duration of tours that are ultimately bound for Europa, they offer delta-v savings and greater scientific return, including the possibility of flying through the plume of one of Io's volcanoes.

09:15 **AAS 09 - 359** **Mission design issues for the european orbiter of EJSM/Laplace : Callisto fly-bys and launch declination issues.**
Yves Langevin, CNRS and Université Paris Sud XI

The EJSM / Laplace proposal has recently been selected as the candidate for a collaboration between NASA and ESA dedicated to outer solar system objects. The ESA contribution is being considered in the framework of the Cosmic Vision program. It is dedicated to the two outer Galilean satellites, with multiple fly-bys of Callisto then an orbital phase around Ganymede. The presentation will focus on the round trip to Callisto between insertion and GOI, sequences of petal and singular transfers providing extensive coverage of Callisto. The launch declination issue which is critical for a launch from Kourou will also be adressed.

09:40 **Break**

10:05 **AAS 09 - 356** **Mission Design for the Titan Saturn System Mission Concept**

Nathan Strange, Thomas Spilker, Damon Landau, Try Lam, Daniel Lyons, Jet Propulsion Laboratory; Jose Guzman, Johns Hopkins Applied Physics Laboratory

In 2008, NASA and ESA commissioned a study of an international flagship-class mission to Titan, Saturn, and Enceladus consisting of a NASA orbiter and two ESA in situ elements, a montgolfière hot air balloon and a lake lander. This paper provides an overview of the trajectory design for this mission, which consists of a solar electric interplanetary trajectory to Saturn, a gravity-assist tour of Titan and Enceladus, delivery of the two in situ elements, Titan aerobraking, and a Titan circular orbit.

10:30 **AAS 09 - 355** **Broad Search For Solar Electric Propulsion Trajectories To Saturn With Gravity Assists**

Try Lam, Damon Landau, and Nathan Strange, Jet Propulsion Laboratory

Solar electric propulsion (SEP) trajectories to Saturn using multiple gravity assists are explored for the joint NASA and ESA Titan Saturn System Mission concept. Results show that these new set of trajectories enable greater performance compared to chemical propulsion with similar gravity assists or SEP without gravity assists. This paper will discuss the method used in finding these interplanetary trajectories and examines variations in the performance for difference SEP systems, flight times, and flyby sequences. The benefits of the SEP trajectories for a mission to Saturn are also discussed.

10:55 **AAS 09 - 358** **Aerobraking at Titan**

Daniel T. Lyons and Nathan J. Strange, Jet Propulsion Laboratory

The proposed Titan Saturn System Mission (TSSM) would launch in 2020 to study the Saturn system. The primary spacecraft would ultimately end up in a low circular science orbit around Titan. This paper will describe the aerobraking phase that is used tosample the atmosphere of Titan at a variety of altitudes and latitudes while using the atmospheric drag to reduce the propellant requirements on the mission. The third body perturbations of Saturn during the aerobraking phase made this an interesting design problem that will be described in the paper.

Session 9: Spacecraft Guidance, Navigation, and Control I

Chair: Kenneth Williams, KinetX, Inc.

08:00 **AAS 09 - 360** **Application of Time Varying Eigensystem Realization Algorithm to Guidance and Control Problems**

M. Majji, M., J. N. Juang,, and J. L. Junkins, Texas A&M University

System identification method called the Time Varying Eigensystem Realization Algorithm is applied to input output experimental data to realize approximate models for the departure motion dynamics about the nominal trajectory of nonlinear models. First problem involves an optimal control problem involving the 2 dimensional motion of a point mass. It is shown that in the presence of unstructured nonlinearities, using experimental data, models governing the departure motion dynamics can be explicitly constructed. These models are subsequently shown to be useful in a perturbation guidance scheme. Subsequent example considers the dynamics of a point mass in a rotating tube apparatus.

08:25 **AAS 09 - 361** **Autonomous And Explicit Real-Time Targeting And Guidance For Lunar Descent And Precision Landing**

Dilmurat Azimov, Emergent Space Technologies, Inc.

Autonomous and explicit real-time targeting and guidance design solutions for future powered lunar descent and precision landing missions are presented. These solutions are based on the development and enhancement of Apollo guidance programs. Detailed andexplicit description of these programs and development of new real-time targeting and guidance design by employing exact and explicit closed-form solutions for finite-thrust arcs are presented. In general, the closed-form solutions provide an integratedreal-time targeting, guidance, navigation and control (TGNC) capability to perform autonomous operations. The solutions are illustrated by the design of descent guidance for mission to Shackleton crater.

08:50 **AAS 09 - 362** **Constrained, Minimum-Time Maneuvers For Cmg Actuated Spacecraft**

Andrew Fleming, Leffler Consulting, LLC; Pooya Sekhavat and I.Michael Ross, US Naval Postgraduate School

In this examination of minimum-time optimal maneuvering of spacecraft equipped with control moment gyros (CMG) we explore the effects of a variety of state, control and path constraints on the optimal control solution and state history. Our goals are two-fold. First we seek to increase the fidelity of the model to more closely resemble the actual physical constraints on a CMG actuated spacecraft. Then, we seek to understand the effects of these constraints on the optimal control solutions by a throughexamination of the open loop optimal control solutions, switching functions and the associated states.

09:15 **AAS 09 - 363** **Nonlinear Adaptive Control Of A Leo Spacecraft Perturbed By Atmospheric Drag,J2 Effect, And Moon Gravity**

Reza Raymond Karimi and Danile Mortari, Texas A&M University

A nonlinear adaptive full state feedback linearization scheme was used to control the perturbed motion of a LEO spacecraft in a three-body problem. The perturbations were caused by atmospheric drag, J2 effect, and the Moon gravitational field. The nominaltrajectory of the spacecraft is known and the difference between the output of the system (current trajectory) and the nominal trajectory is the basis of designing of the controllers. Finally two scenarios were considered to validate the performance of the designed controllers.

09:40 **Break**

10:05 **AAS 09 - 364** **Closed-Form Solutions To The Minimum-Total-Delta-V-Squared Lambert's Problem**
Jeremy Davis, Martin Avendano, and Daniele Mortari; Texas A&M University

A closed form solution to the Minimum-Total-Delta-V-Squared Lambert problem between two assigned positions in two general orbits is presented. Motivation comes from the need of computing optimal orbit transfer matrices for solving the re-configuration problem of satellite constellations and the complexity associated in facing this problem with the minimization of Total-Delta-V-Squared. The difference between a two-impulse Total-Delta-V-Squared and Total-Delta-V orbit transfer is bounded. The solving equation of Minimum-Total-Delta-V-Squared Lambert problem is a quartic polynomial in term of the angular momentum modulus of the optimal transfer orbit. Root selection is discussed and the singular case, occurring when the initial and final radii are parallel,is analytically solved. One numerical example is given for the general case (transfer between no-coplanar elliptical orbits).

10:30 **AAS 09 - 365** **Comparison between the Mission Design and Reconstruction of the Cassini-Huygens Trajectories and Maneuvers**
P. W. Stumpf, C.G. Ballard, E. M. Gist, Y. Hahn, J. B. Jones, S. V. Wagner, and P. N. Williams, Jet Propulsion Laboratory

During the Cassini-Huygens orbital phase, the maneuver team collected data to determine the maneuver prediction accuracy and maneuver implementation accuracy as well as data to assess the ability of the navigation team to adhere to the reference trajectory. During the mission planning stage, questions arose as to what level the spacecraft would be able to maintain the reference trajectory and what value of statistical maneuver cost would be needed for each encounter. Conservative answers were provided dueto the lack of similar data from past projects. Data obtained by the maneuver team and analysis that revisits these questions is presented.

10:55 **AAS 09 - 366** **Continuous-Time Bilinear System Identification Using Repeated Experiments**
Majji, M., Juang, J. N., Junkins, J. L., Texas A&M University

A novel method for the identification of continuous time bilinear system plant models, from the input output data associated with multiple experiments is presented. Making use of the recent advances in bilinear system identification, the current work documents the advantage of utilizing multiple experiments and sets up a procedure to obtain bilinear system models. It is shown that the special pulse inputs employed by earlier research can be avoided and accurate identification of the continuous time plantmodel is possible by performing multiple experiments incorporating a class of control input sequences.

11:20 **AAS 09 - 367** **A New Approach To Underweight Lidar Measurements**
Renato Zanetti, The Charles Stark Draper Laboratory; Kyle J. DeMars and Robert H. Bishop, The University of Texas at Austin

Underweighting is an ad hoc technique to reduce the Kalman filter update in order to compensate for unaccounted second order terms in the Taylor series expansion of the filter's residual. Existing underweighting techniques are revisited, these techniquesheavily rely on trial and error to finalize the design. For the case of underweighting LIDAR measurements, a new scheme is introduced to aid the tuning of the filter, obtaining a viable underweighting coefficient in a single run.

Session 10: Conjunction Assessment I

Chair: Robert Hall, AGI

13:30 AAS 09 - 368 Analysis of the Iridium 33-Cosmos 2251 Collision

T.S. Kelso, Center for Space Standards & Innovation (CSSI)

On 2009 February 10, Iridium 33--an operational US communications satellite in low-Earth orbit--was struck and destroyed by Cosmos 2251--a long-defunct Russian communications satellite. This is the first time since the dawn of the Space Age that two satellites have collided in orbit. To better understand the circumstances of this event and the ramifications for avoiding similar events in the future, this paper provides a detailed analysis of the predictions leading up to the collision, using various datasources, and looks in detail at the collision, the evolution of the debris clouds, and the long-term implications for satellite operations.

13:55 AAS 09 - 369 It's Not A Big Sky After All: Justification For A Close Approach Prediction And Risk Assessment Process

Ryan Frigm and David McKinley, a.i. solutions, Inc.; Lauri K. Newman, NASA Goddard Space Flight Center

There is often skepticism about the need for Conjunction Assessment from mission operators that invest in the "big sky theory", which states that the likelihood of a collision is so small that it can be neglected. On 10 February 2009, the collision between Iridium 33 and COSMOS 2251 provided an indication that this theory is becoming invalid and that a CA process should be considered for all missions. This paper presents statistics of the effect of the Iridium/COSMOS collision on NASA's Earth Science Constellation as well as results of analyses which characterize the debris environment for NASA's robotic missions.

14:20 AAS 09 - 370 Forensic Reconstructions of the Fengyun 1C and Iridium 33 / Cosmos 2251 Satellite Breakups

Johannes Hacker, Emergent Space Technologies, Inc.

Satellite breakups due to explosions have been modeled based upon empirical data in the past. But empirical data on breakups caused by hypervelocity impact have only become available due to recent unfortunate events. A first order forensic reconstructionof the Iridium 33 / Cosmos 2251 collision similar to one conducted on FY-1C is presented. In addition, a higher order reconstruction for both events will be presented. Methods of determining ballistic coefficient data from TLE data will be applied. Higher order reconstructions of the FY-1C and the Iridium 33 / Cosmos 2251 breakup events will be presented.

14:45 AAS 09 - 371 Correlating Spacecraft Debris from Various Tracking Measurements

Timothy Craychee and John Carrico, Applied Defense Solutions; Richard Hujsak Analytical Graphics Inc.

With the collision of Iridium 33 and Cosmos 2251 correlating the debris, created by the impact, between various tracking measurements is a difficult problem. While it is possible to discern how many pieces of debris were created, consistently identifyingeach individual piece from one set of tracking data to the next is a long and complex problem. The purpose of this paper is to demonstrate a new method of correlating tracking data to the individual pieces of debris, and to generate a high precision position and velocity for each piece. This correlated data would then used by an orbit determination tool to determine and predict the orbit of the various pieces of debris.

15:10 **Break**

15:35 **AAS 09 - 372** **A Description Of Filters For Minimizing The Time Required For Orbital Conjunction Computations**
James Woodburn, Vincent Coppola and Frank Stoner, Analytical Graphics, Inc.

A series of computational filters designed to minimize the time required for identification of orbital conjunctions is presented. The goal of the filters is to quickly eliminate as many pair-wise combinations of satellites as possible from consideration during the search for orbital conjunctions. Difficulties associated with the original description of these filters will be illustrated and improved implementations described. Finally the computational advantage associated with each filter will be illustrated in terms of the time required to solve the all on all conjunction problem.

16:00 **AAS 09 - 373** **A Single Conjunction Risk Assessment Metric: The F-value**
Ryan Clayton Frigm, a.i. solutions Inc.

The Conjunction Assessment task at NASA Goddard Space Flight Center provides conjunction risk assessment for many NASA robotic missions. These risk assessments are based on several figures of merit, such as miss distance, Probability of Collision (Pc), and orbit determination solution quality. The goal of this analysis is to provide a single, stable risk level index metric that can easily convey the level of risk without all the technical details. The proposed index is called the conjunction F-value.This paper presents the concept of the F-value and the tuning of the metric for use in routine Conjunction Assessment operations.

16:25 **AAS 09 - 374** **Assessing Satellite Conjunctions for the Entire Space Catalog using COTS Multi-core Processor Hardware**
Vincent Coppola , Sylvain Dupont , Kevin Ring , and Frank Stoner, Analytical Graphics Inc.

Recent events have shown the importance of conducting conjunction assessments on a continual regular basis for operational spacecraft. We study the feasibility of assessing the entire space object catalog (i.e., an all-on-all assessment) for 1 and 5 day analysis periods, using both low and high fidelity ephemerides, using COTS software and COTS multi-core processor hardware. We show that a catalog of 12,000 space objects (involving almost 72 million pairings) can be assessed within one hour and thus incorporated into an operational environment. The impact on the assessment of larger catalogs (e.g., 20K or 100K objects) will also be discussed.

16:50 **AAS 09 - 375** **The Collision Risk Assessment & Risk Mitigation Process for the NPP/NPOESS Missions**
Amy Bleich, General Dynamics, Inc.; Matthew Duncan and Josh Wysack, a.i. solutions, Inc.

Orbital debris poses a significant threat to spacecraft health and safety. The majority of the debris population lies in low earth orbit with the peak near an altitude of 800 km. Since the National Polar-orbiting Operational Environmental Satellite System (NPOESS) intends to operate in a sun-synchronous altitude of 824 km, the NPOESS Integrated Program Office (IPO) has established a risk assessment and risk mitigation process for the NPOESS constellation. This paper describes the tools and processes used to analyze and mitigate collision threats for the NPP (NPOESS Preparatory Project) and NPOESS mission set.

Session 11: Trajectory Optimization II

Chair: Dr. Anastassios Petropoulos, Jet Propulsion Laboratory

13:30 **AAS 09 - 376** **Lunar Orbit Insertion from a Fixed Free Return**

Mark C. Jesick and Cesar A. Ocampo, The University of Texas at Austin; Gerald L. Condon, NASA Johnson Space Center

This paper combines lunar free return trajectories with lunar orbit insertion (LOI) sequences to provide both crew safety and selenographic versatility. Because future missions necessitate global lunar access, the required spacecraft plane change at themoon may be large enough that a multi-maneuver sequence offers velocity impulse cost savings. This paper develops a targeting and optimization procedure to transfer a spacecraft from a lunar free return trajectory to any closed lunar orbit through a multi-maneuver LOI sequence. Thus, a safe earth-return for crew is guaranteed while not compromising the ability to achieve any lunar orbit.

13:55 **AAS 09 - 377** **Shrinking the V-infinity Sphere: Endgame Strategies for Planetary Moon Orbiters**

Ryan C. Woolley and Daniel J. Scheeres, University of Colorado

Delivering an orbiter to a planetary moon such as Europa or Titan requires an excessive amount of fuel if the trajectory is not carefully and cleverly planned. Investigations of endgame strategies such as V-infinity leveraging in conjunction with resonant orbits have shown promising results. Making use of a new graphical technique, it is possible to better visualize the optimal use of V-infinity leveraging maneuvers and fly-bys to reduce hyperbolic excess velocity and ultimately capture into orbit. Initial numerical results show that the optimal location for performing V-infinity reduction maneuvers is not necessarily at apoapsis, due to targeting constraints.

14:20 **AAS 09 - 378** **An Approach for Computing Single-Spacecraft Pole-Sitter Trajectories**

Martin T. Ozimek, Daniel J. Grebow, and Kathleen C. Howell, Purdue University

Designing trajectories in a chaotic system such as the restricted three-body problem suggests that constant surveillance of a given surface region of the smaller primary might be achieved with just one spacecraft in the presence of a small control input.A systematic collocation method is presented that maintains direct line-of-sight with a target surface area including path constraints such as minimum elevation angle and maximum altitude. Low-thrust from solar sails and electric propulsion are examined, as well as potential solutions with small impulsive maneuvers. The methods are generalized for any system and example trajectories are included.

14:45 **AAS 09 - 379** **Kepler Trajectory Design**

Roby Wilson, Min-Kun Chung, and Julie Kangas, Jet Propulsion Laboratory

The Kepler mission launched on March 6, 2009, placing the spacecraft in an Earth-trailing heliocentric orbit. The primary objective of the Kepler mission is to better understand the origins of the Solar System by determining the frequency of Earth-like planets around other stars. The Kepler science instrument itself is a highly sensitive photometer that will conduct a census of extra-solar terrestrial planets by observing the dimming of light caused by planetary transits in a fixed portion of the sky.This paper will provide a brief overview of the mission and then describe in detail the design of the Earth-trailing trajectory to support this planet finding survey.

15:10 **Break**

15:35 **AAS 09 - 380** **Global Performance Characterization of the Three Burn Trans-Earth Injection Maneuver Sequence over the Lunar Nodal Cycle**

Jacob Williams and Elizabeth C. Davis, Engineering and Science Contract Group; David E. Lee, Gerald L. Condon and Tim Dawn, NASA Johnson Space Center; Min Qu, Analytical Mechanics Associates, Inc.

The Orion spacecraft will be required to perform a three-burn trans-Earth injection (TEI) maneuver sequence to return to Earth from low lunar orbit. The origin of this approach lies in the Constellation Program requirements for access to any lunar landing site location combined with anytime lunar departure. This paper documents the development of optimized databases used to rapidly model the performance requirements of the TEI three-burn sequence for an extremely large number of mission cases. It alsodiscusses performance results for lunar departures covering a complete 18.6 year lunar nodal cycle as well as general characteristics of the optimized three-burn TEI sequence.

16:00 **AAS 09 - 381** **Variational Model for the Optimization of Constrained Finite-Burn Escape Sequences**

Cesar Ocampo and Jean-Philippe Munoz, University of Texas at Austin

This paper presents the derivation of the variational equations associated with a one or three-finite burn escape sequence from a lunar parking orbit to a hyperbolic trajectory. The variational equations are obtained via a general method, using the state-transition matrix associated with an augmented state-vector that contains the position, velocity and mass of the spacecraft, the thrust magnitude and direction, and the exhaust velocity. These equations allow us to compute the gradients required to optimize the cost of the escape transfer using a Sequential Quadratic Program. Numerical simulations are presented comparing the performance of these gradients to numerically approximated ones.

16:25 **AAS 09 - 382** **Preliminary Trajectory Design For The Artemis Lunar Mission**

Stephen B. Broschart, Min-Kun J. Chung, Sara J. Hatch, Jin H. Ma and Theodore H. Sweetser, Jet Propulsion Laboratory; Vassilis Angelopoulos, UCLA

The ARTEMIS mission is an extension to the THEMIS mission that will send two of the Earth-orbiting THEMIS probes on a circuitous route to the Moon beginning in July 2009. This paper describes the ARTEMIS trajectory designs proposed to the NASA Senior Review in April 2008 (and accepted in May 2008). The trajectory design is very challenging due to the constraints imposed by the capabilities of the orbiting hardware. Nonetheless, the mission science objectives are successfully addressed by two unique trajectory solutions which include multiple lunar approaches, lunar flybys, low-energy trajectory segments, lunar Lissajous orbits, and low-lunar orbits.

Session 12: Attitude Dynamics, Determination, and Control II

Chair: William Cerven, The Aerospace Corporation

08:25 **AAS 09 - 383** **High Dynamic Range Imaging For High Performance Star Tracking**
Brien R. Flewelling, Troy A. Henderson, and Drew P. Woodbury, Texas A&M University

A method is presented for the generation of high dynamic range imagery for the purposes of high performance star tracking. Star trackers are limited today when high energy sources are present within or near the field of view. Extending the dynamic range using multiple exposures allows for accurate centroids to be obtained for a larger range of stars. The HDR technique will allow star trackers to extend their operational range to scenes which include larger energy ranges than is currently observed today.

08:50 **AAS 09 - 384** **Low-Cost Approaches to Star Tracker Lab Testing**
Tom Dzamba and John Enright, Ryerson University

Rather than the more common use of star trackers for precision estimates of attitude, microsatellites utilize the pattern recognition abilities of star trackers to attain a robust, 3-axis attitude solution. A method of testing star trackers for this application is to project star fields onto a surface and image them using the prototype sensor. Many complications arise as the geometry of the setup is difficult to measure and align. To simplify this procedure, an approach has been developed to semi-automate the calibration of this test bed apparatus, emphasizing minimal setup while still retaining accuracy of less than an arc minute.

09:15 **AAS 09 - 385** **Information Theoretic Weighting For Robust Star Centroiding**
Brien R. Flewelling and Daniele Mortari, Texas A&M University

A statistical methodology for the global and local analysis of star tracker image content is presented which is based on the A-Contrario framework. A level set analysis using this methodology effectively weights signals with a confidence interval based onthe information content. Globally this analysis can represent the non-planar noise floor associated with the sky background. Locally, this analysis can automatically define the annulus which represents the partial pixels associated with the boundary between signal and noise. The performance of centroiding with information theoretic weighting is evaluated compared to traditional thresholding methods for simulated and real star tracker images.

09:40 **Break**

10:05 **AAS 09 - 386** **On The Relationships Between Proofs Of Convergence In Continous And Discrete Time Iterative Learning Control**
Joe W. Yeol and Richard W. Longman, Columbia University

Iterative learning control (ILC) iterates with the command to a feedback control system, aiming to converge to zero tracking error following a specific command. Spacecraft applications include getting zero error in a desired scanning maneuver that will berepeated. The ILC literature has two mail development streams, one in continuous time which can handle nonlinear systems but are impractical to implement, the other in discrete time. The proofs of convergence are very different for each approach. Here webuild a bridge to connect the two approaches. In the process we aim to make ILC for nonlinear discrete time systems.

10:30 AAS 09 - 387 Identification of Linear Time-Varying Systems By Canonical Representation

Minh Q. Phan, Dartmouth College; Richard W. Longman, Columbia University; Jer-Nan Juang,
National Cheng-Kung University

This paper presents a method to identify time-varying state-space models by canonical representation. Unlike recent OKID/ERA based methods which work through the observer Markov parameters, this method uses the canonical forms to derive the time-varyingstate-space models. The paper describes the relationship between a time-varying state-space model and a time-varying auto-regressive moving-average (ARX) model and various canonical forms that convert a time-varying ARX model to a time-varying state-space model. Numerical examples are provided to illustrate the developed identification method.

10:55 AAS 09 - 388 Sliding Mode Observer for Spacecraft Attitude Estimation: A Special Case

Mohamed M. Aly, Old Dominion University; Hossam Eldin-A. Abdel Fatah and
Ahmed Bahgat, Cairo University

This paper presents a sliding mode observer (SMO), that can be used for moderate-accuracy attitude determination systems for LEO Earth-pointing spacecraft (s/c), which is typically using Gyroscopes, Earth, and Sun sensors for attitude sensing, this is toprovide a substitute for the yaw data in case of the s/c eclipse periods or limited field of views. The nonlinear observability for this system is investigated analytically via the calculation of Lie derivatives to check the possibility of the system states estimation. The performance of the SMO observer is presented, the stability for the SMO is proven and SMO enhanced estimates is shown.

Session 13: Formation Flying

Chair: Brian Gunter, Delft University of Technology

08:00 **AAS 09 - 389** **Charged Spacecraft Formations: A Trade Study on Coulomb and Lorentz Forces**

George E. Pollock, Joseph W. Gangestad, and James M. Longuski, Purdue University

Electrostatically charged spacecraft have been proposed for formation flying applications in LEO and GEO. The inter-spacecraft Coulomb force acts internally to the formation while the geomagnetic Lorentz force provides an external perturbation. A relativemotion dynamical model is developed that includes the effect of both Coulomb and Lorentz forces. The Lorentz force introduces a small perturbation at high altitudes (where the Coulomb force is dominant) while the Coulomb force has negligible effect in LEO. Elliptical orbits permit a set of charged spacecraft to use a combination of these electromagnetic forces for both formation and orbit control.

08:25 **AAS 09 - 390** **One-Dimensional Position Feedback Control Experiments Using the Coulomb Testbed**

Carl R. Seubert and Hanspeter Schaub, University of Colorado

The Coulomb testbed has successfully demonstrated preliminary studies of electrostatic relative motion. The knowledge and technology developed with this testbed could ultimately be used to efficiently control spacecraft flying in close formation. This paper describes the next level of testing conducted on the near-frictionless one-dimensional (1-D) Coulomb testbed. Modifications and updates to the testbed have been performed to further quantify and mitigate disturbance forces. Accurate position sensing allows the implementation of real-time feedback control on cart motion. Results of Coulomb actuated cart motion experiments are presented, including autonomously controlled 1-D constrained orbit-similar scenarios.

08:50 **AAS 09 - 391** **Coulomb Feedback Control of a Triangular 3-Vehicle Cluster**

Shuquan Wang and Hanspeter Schuab, University of Colorado

This paper studies a three-body Coulomb virtual structure control problem. For a formation of three spacecraft flying freely in deep space, Coulomb forces are used to stabilize the configuration of the formation to some desired configuration. A two-sideswitched control strategy is developed to always control the worst two sides instead of controlling both three sides at once to ensure the implementable charge control solution. The stability of the switched control is challenging to proof analytically in the presence of discrete control time steps. Using multiple Lyapunov functions analysis tool, the switched control strategy is setup in the way that the activated Lyapunov function candidate is decreasing rapidly enough to to compensate for a potentially increased amount during the last control cycle.

09:15 **AAS 09 - 392** **A Peer-to-Peer Refueling Strategy using Low-thrust Propulsion**

Nitin Arora, Atri Dutta, and Ryan Russell, Georgia Institute of Technology

In this paper, we address the problem of minimum-fuel, time-fixed, low-thrust rendezvous problem, with the particular aim of developing a solver to determine optimal low-thrust Peer-to-Peer (P2P) maneuvers, which will be integral part of all distributed low-thrust servicing missions for multiple satellites. We develop the solver based on an indirect optimization technique and utilize the shooting method to solve the two-point boundary value problems corresponding to the forward and return trips of a P2P maneuver. The development of this solver is a first step in the direction of studying low-thrust servicing missions for multiple satellites in circular constellations.

09:40 **Break**

10:05 **AAS 09 - 393** **Nonlinear Coulomb Feedback Control of a Two Spacecraft Virtual Structure**
Shuquan Wang and Hanspeter Schaub, University of Colorado at Boulder.

This paper studies a two-spacecraft Coulomb virtual structure control problem. Only Coulomb forces are utilized to control the configuration of the two-spacecraft formation flying in a geostationary orbit. At first the separation distance equation of motion is derived. A Lyapunov-based nonlinear feedback control algorithm is developed to stabilize the separation distance to a desired value. In this development both the orbital motion of spacecraft about a planet, as well as the partial electrostatic shielding of a space plasma environment are considered. Without the full inertial position feedback term the control does not converge. However, the shape tracking errors are still bounded and estimates of these bounds are developed.

10:30 **AAS 09 - 420** **Formation Flying Control Implementation in Highly Elliptical Orbits**
Peter Bainum, Howard University; Pedro A. Capó-Lugo, NASA Marshall

The Tschauner-Hempel (TH) equations express the motion of a pair of satellites in highly elliptical orbits. The TH equations are discretized in the true anomaly domain because it will be used in a digital controller. During this process, the computationaltime can be reduced by selecting a suitable sampling interval. The objective of this paper is to implement the discrete TH equations and the controller in the computer onboard the satellite. These equations are expressed in the true anomaly domain; for this reason, a mathematical relation will be formulated to determine the time instead of the true anomaly.

10:55 **AAS 09 - 394** **Rf Based Navigation For Prisma And Other Formation Flying Missions In Earth Orbits**
Michel Delpech, Pierre-Yves Guidotti, Thomas Grelier, Sophie Djalal, and Jon Harr, Centre National d'Etudes Spatiales

PRISMA, a bi-satellite technology mission to be flown in November 2009 (funded by SNSB with participation from several European partners) will demonstrate in LEO autonomous rendezvous and Formation Flying (FF) techniques. CNES provides a Radio Frequency sensor and GNC software to perform some FF experiments based on a technology that will be tested in space for the first time. The paper will describe the major technical challenges related to the design and validation of an autonomous navigation system involving tight interaction between RF sensor and GNC software and will discuss how this function can be reused for future FF missions.

Session 14: Dynamical Systems Theory Applied to Space Flight

Chair: Dr. Kathleen Howell, Purdue University

08:00 **AAS 09 - 395** **KAM Tori Normal Coordinates**
William E. Wiesel, Air Force Institute of Technology

To date, KAM tori have been obtained by fitting an integrated trajectory, and contain only new coordinate information. The theory of KAM tori is extended to make them "thick", introducing new coordinates Q_i that are linear in time, and new momenta P_i that are constant. The Hamiltonian reduces to a quadratic form, and appears to be decoupled for solvable (separable) systems, but still coupled in the momenta for non-separable systems. This should make it possible to treat a KAM torus as a classical orbit, with a full set of dynamical variables and a Hamitonian function.

08:25 **AAS 09 - 396** **Instability Characterization of Spacecrafts Near Stable Manifolds**
Ima Alizadeh and Bejamin Villac, University of California, Irvine

Recent endeavors in space exploration of the outer system raised new stability questions for the motion of spacecraft in strongly perturbed environments. In order to provide sufficient safety margins to meet the various mission requirements, planetary protection concerns required the availability of a recovery time at any point of the trajectory. In this paper the application of Lyapunov exponents is presented to characterize this notion and compared to the numerical simulations for two sample periodic orbit families. The results obtained shows significant computational reduction for stability analysis of trajectories in unstable orbital environments. This paper develops the theoretical basis of recovery time notion to be used as a tool for mission designers to quickly evaluate and design trajectories that require good orbital stability characteristics.

08:50 **AAS 09 - 397** **Numerical Exploration of Small Body Orbiter Dynamics Using Chaoticity Indicators**
Benjamin F. Villac and Katherine Yi-Yin Liu, University of California, Irvine;
Stephen B. Broschart, Jet Propulsion Laboratory

Previous research indicated the feasibility and usefulness of chaoticity indicat or maps to analyze the complex dynamics associated with realistic small body orbiters models. This paper explores further this method by exploring different indicators, suchas orthogonal FLI, mean FLI and other sensitivity indicators to reveal additional dynamical structure (such as invariant manifolds and periodic orbits) that are relevant to spacecraft mission trajectory design. This study allows us to better characterizethe size of the stability region in state space and use such information in a mission design context.

09:15 **AAS 09 - 398** **Locally Optimal Transfers Between Libration Point Orbits Using Invariant Manifolds**
Kathryn Davis, University of Colorado, Rodney Anderson, Daniel Scheeres, and George Born, University of Colorado

A method is developed for constructing locally optimal transfer trajectories between libration point orbits with different energies. The unstable manifold of the first orbit is connected to the stable manifold of the second orbit by the execution of two or more maneuvers. Two-body parameters define the selection of the unstable and stable manifold trajectories used for the transfer. The maneuver locations along the manifolds are determined by an application of primer vector theory. This method produces fuel costs up to 73% less than transfers trajectories that do not employ the use of manifolds.

09:40 **Break**

10:05 AAS 09 - 399 Families of Transfer Trajectories to Distant Retrograde Orbits, Part 1: Transfers to Periodic Orbits

Christopher J. Scott and David B. Spencer

The existence of collision orbits in the vicinity of the distant retrograde region is well-documented in works involving satellite capture. This study utilizes the orderly arrangement of collision regions and a simple dynamical analysis to facilitate a focused sampling of phase space. This limited sampling provides an accurate guess for differential correction and numerical continuation algorithms for an arbitrary number of transfer types. A procedure is outlined that calculates favorable insertion points in terms of transfer time and delta-V. The relationship between families of transfer orbits and the morphology of phase space near the distant retrograde region is discussed.

10:30 AAS 09 - 400 Families of Transfer Trajectories to Distant Retrograde Orbits, Part 2: Single Impulse Transfers and Transfers to Quasi-periodic Orbits

Christopher J. Scott and David B. Spencer, The Pennsylvania State University

This study extends techniques developed in Ref. 1 to single impulse transfers and transfers to quasi-periodic orbits. A single impulse transfer takes the spacecraft to the fringes of the stability region where it can reside for an extended period of time. These transfers are useful for spacecraft with no propulsive mechanism. The latter transfer utilizes two impulsive burns to insert into a quasi-periodic orbit within the stable distant retrograde region. For the second maneuver these transfers have the benefit of fuel savings over comparable transfers to the central periodic orbit.

10:55 AAS 09 - 402 New Families of Multi-Revolution Terminator Orbits Near Small Bodies

Stephen B. Broschart, Jet Propulsion Laboratory; Daniel J. Scheeres, University of Colorado at Boulder; Benjamin F. Villac, University of California at Irvine

Terminator orbits known to be robust under the influence of a large solar radiation pressureperturbation and a weak and irregular gravitational potential. These orbits are ideal for missions that require long-term stable motion near small asteroids and comets. This paper identifies a number of new classes of multi-revolution terminator orbits and studies their geometry and stability characteristics. These orbits may be used to improve observation geometry for scientific observations compared to terminatororbits while preserving long-term stable and robust motion.

Session 15: Spacecraft Guidance, Navigation, and Control II

Chair: Dr. Peter Lai, The Aerospace Corporation

13:30 **AAS 09 - 403** **Failure Robust Thruster Commanding for Space Vehicles Control**

Riccardo Bevilacqua and Marcello Romano, Naval Postgraduate School; Fabio Curti, Sapienza University of Rome

This paper faces the problem of controlling the six-degrees-of-freedom dynamics of a spacecraft by employing on-off thrusters only, in case of actuators unpredictable failures. Our methodology starts from the assumption that one or more thrusters can suddenly fail, and that the logic driving the translational and rotational dynamics does not have any information on which actuators have stopped responding. The final goal is to guarantee robust controllability of the space vehicle through the failures, limiting the malfunctioning detection schemes to a minimum or even not requiring any at all. Laboratory experimentation is performed to support the theory.

13:55 **AAS 09 - 404** **Nonlinear Monte Carlo Mission Simulation and Statistical Analysis**

Christopher L. Potts, Richard M. Kelly, and Troy D. Goodson, Jet Propulsion Laboratory

Monte Carlo mission simulations combine a priori and predicted knowledge uncertainties, flight path control strategies, error models, trajectory sensitivities, and ground design schedules to evaluate and enhance mission system performance. Nonlinear modeling capabilities are required to support advanced mission types that include low-thrust, orbiter mapping, low-energy or third body trajectory variation, and Lissajous orbits. FARO is a prototype software system that provides nonlinear Monte Carlo missionsimulation and continuous statistical analysis capabilities with a multi-mission architecture that supports both low- and high-thrust propulsion. The prototype system is being used to investigate sensitivities and operation planning for the Dawn and Grailmissions.

14:20 **AAS 09 - 405** **Pseudospectral Optimal Control on Arbitrary Grids**

Qi Gong, Univ. of California, Santa Cruz; I. Michael Ross and Fariba Fahroo, Naval Postgraduate School

In this paper we present new results for PS methods over arbitrary grids. These results provide a way to compare performance between different PS methods and suggest guidelines to choose the right grids and discretization approaches for solving optimal control problems. The full paper reveals hidden properties of different types of PS methods and paves the way to construct more efficient algorithms for solving different types of optimal control problems.

14:45 **AAS 09 - 406** **Simultaneous Computation of Optimal Trajectories and their Sensitivities**

Chris McCrate and Srinivas Vadali, Texas A&M University

A method for solving optimal feedback control problems for a class of non-linear, fixed time, dynamical systems is presented. This method allows for the computation of the trajectory and the associated sensitivities simultaneously, without iterations, for weakly nonlinear problems. For more complex problems, a waypoint scheme is utilized, in order to limit the time interval between segments of the trajectory. The applications of this method are demonstrated via several examples, including a reentry problem involving an aerodynamic heat loading performance index.

15:10 **Break**

15:35 **AAS 09 - 407** **On the Curse of Dimensionality in Fokker-Planck Equation**
Suman Chakravorty, John Junkins, and Mrinal Kumar, Texas A&M University

The curse of dimensionality in context of the Fokker-Planck equation is addressed in this paper. A survey of existing numerical methods for discretizing the Fokker-Planck equation is conducted. Exponential increase in size of the discretized problem withincreasing dimensionality of the underlying state-space is discussed. A local approximation technique based on the particle-partition of unity finite element method (pPUFEM), coupled with local p-refinement is presented as a tool for making the discretized problem size independent of system dimensionality, hence breaking the curse. Quasi Monte Carlo integration is employed to evaluate high dimensional integrals appearing in the variational equations. Superiority of the current method is illustrated with examples for systems having up to 6 dimensional state space using modest computational resources.

16:00 **AAS 09 - 408** **Trajectory Reconstruction of the ST-9 Sounding Rocket Experiment Using IMU and Landmark Data**
R.S. Park, S. Bhaskaran, J.J. Bordi, Y. Cheng, A.J. Johnson, G.L. Kruizinga, M.E. Lisano, W.M. Owen, A.A. Wolf, Jet Propulsion Laboratory

This paper presents a trajectory reconstruction of the ST-9 sounding rocket experiment using IMU and landmark data. The raw IMU accelerometer and gyro data are first converted into acceleration and quaternion and are used in trajectory integration. The descent images are pre-processed using map-matching algorithm and unique landmarks for each image are created. A batch least-squares filter is appand estimate the position, velocity, camera orientation of each image, and stochastic acceleration. The reconstructed trajectory is compared with the GPS data and the uncertainties and state differences are presented.

16:25 **AAS 09 - 425** **Approximate Minimum-time Control Versus the PEG Control for Lunar Ascent**
David G. Hull, University of Texas at Austin

The minimum-time control for constant-thrust lunar ascent is simplified by assuming that the thrust inclination is small. Because the downrange cannot be prescribed, the resulting control obeys a linear tangent law. The approximate minimum-time control can be determined completely analytically, that is, no iterations are required to obtain the control. Powered Explicit Guidance (PEG) is reviewed, and it is shown that the downrange cannot be prescribed. However, the control is made to satisfy a bilineartangent law, so that the PEG control is not the minimum-time (minimum-fuel) control. Also, it is not completely analytical since an iteration is needed to calculate the final time. However, both controls used in a sample and hold guidance scheme perform equally well.

Session 16: Conjunction Assessment II

Chair: Robert Hall, AGI

13:30 **AAS 09 - 409** **Discriminating Threatening Conjunctions with Data Fusion Principles**
Salvatore Alfano, David Finkleman, and Tim Carrico, Analytical Graphics, Inc.

The objective of this paper is to apply information theory and data fusion principles to discriminating the most important satellite conjunctions. This work was prompted by the Iridium – Cosmos collision. Significance of predicted conjunctions is now determined from single assessments based on current orbit data. Attention focuses on the few most probable conjunctions at each reporting interval. Highest probabilities on previous assessment may be supplanted by currently more likely events. Conjunctions that demanded attention previously still deserve attention. We will demonstrate assessment techniques that fuse past reports, information about partners, and estimates of the consequences.

13:55 **AAS 09 - 410** **Detection Performance Assessment For Collision Risk Algorithms**
Stéphanie Delavault and Paul Legendre, CNES

Several methods have been developed at CNES for operational collision risk assessment. It has then become necessary to find a generic criterion to evaluate their performance, in order to compare them and to set appropriate thresholds. A “Detection Performance Assessment” algorithm has thus been developed. It consists in a double criterion : first we compute the number of daily alerts, second we evaluate the detection rate on a set of fictitious collision events. A trade-off is then to be found between both criteria. This paper describes this performance assessment method and gives some results of comparison and threshold setting.

14:20 **AAS 09 - 411** **Hazard Evaluation of the Space Debris in the Geostationary Orbit**
Jorge Martins do Nascimento, Instituto Nacional de Pesquisas Espaciais, BRAZIL

The goal of this paper is to discuss the Hazard Evaluation or the space Debris in the Geostationary Orbit, the adoption of mitigation measures for using the GEO orbit and to raise the possibility of adopting a concept of "state of the art" in regard to the remains of the third stages of rocket and engines used in the heydays of transfer orbits as well as the disposal of communication satellites at the end of its useful life.

14:45 **AAS 09 - 412** **Examination of Nonlinearity Based on the Second Order Expansion of the Orbit State Transition**
Sergei Tanygin, Analytical Graphics, Inc.

The nonlinearity of dynamical systems is examined based on the second order expansion of their state transition. The analytical transitive Hessians are derived for Keplerian orbits using universal variable formulation. The second order bias and nonlinearity measures are derived based on the Hessians. Their possible applications for batch and sequential orbit determination as well as for improved long-term uncertainty propagation during conjunction analysis are discussed. The analytical results are validated numerically using several types of orbits.

15:10 **Break**

15:35 **AAS 09 - 413** **Reexamining Probability Dilution**
Joseph (Joe) H. Frisbee, Jr. , United Space Alliance, LLC

In the last several years the concept of "Probability Dilution" or "Dilution of Probability" has been presented in the literature on satellite and orbital debris collision risk analysis. "Probability Dilution" proposes a quality criterion for accepting or rejecting a probability of collision risk estimate on the basis of where the probability estimate occurs with respect to the estimated maximum probability during the close approach event. In this paper evidence will be offered for why this criterion has no supportable basis. The evidence presented will consist of logical arguments supported by numerical examples and figures.

16:00 **AAS 09 - 414** **Launch Collision Avoidance**
Felix R. Hoots, The Aerospace Corporation

Aerospace currently provides operational analysis to determine launch window times with minimal collision risk to on-orbit satellites. The current process is numerically intensive and may exceed computational capacity or timeline constraints as the satellite catalog and launch frequency grows. We have developed more sophisticated and efficient analytical processing algorithms to be able to meet planning and operational timelines for launch collision avoidance for our customers. The new analytical method provides excellent agreement with the current numerical method with a computer runtime reduction by a factor of 100 or more.

16:25 **AAS 09 - 415** **Anti-Satellite Engagement Vulnerability**
Salvatore Alfano, Center for Space Standards and Innovation

This work uses simple orbital dynamics to initially assess the vulnerability of a satellite to an anti-satellite missile. This vulnerability can be represented as an engagement volume for a specific interceptor missile relative to its launch platform or,alternately, as a geographical footprint relative to satellite position that encompasses all possible launcher locations. Two engagement solutions are found that account for spherical earth rotation. One solution finds the maximum interceptor range foran ascent-only trajectory while the other solution accommodates a descending trajectory. These preliminary solutions are formulated to address ground-, sea-, or air-launched anti-satellite missiles.

16:50 **AAS 09 - 416** **Space Situation Monitoring Laboratory: An Integrated Web-Based Environment for Space Environment Information and Analysis**
William Ailor, John Coggi, Thaddeus Cooper, Justin McNeill, Rusell Patera, and Raymond Swartz, The Aerospace Corporation

The Space Situation Monitoring Laboratory (SSML) is a prototype, web-based system designed to detect, display, monitor, and archive anomalous events and provide automated notifications to researchers and engineers. The system employs new algorithms and tools for the monitoring, analysis, and study of the space environment. SSML includes information on satellite ephemeris, predicted satellite closest approaches, space weather, and satellite orbital changes that are indicative of maneuvers, collisions, explosions, or even atmospheric effects. The system uses displays and visualizations with web services infrastructure to present information in an intuitive fashion that lead to a broader understanding of the current satellite environment.

Session 17: Satellite Constellations/Tethered Satellites

Chair: Dr. Daniele Mortari, Texas A&M University

13:30 **AAS 09 - 417** **A Preliminary Study of the Dynamics and Control of the UltraSail Cubesat**
Andrew Pukniel, Victoria Coverstone, and Rodney Burton, University of Illinois at Urbana-Champaign

The proposed study addresses two issues related to slow emergence of solar sailing as a viable space propulsion method. The low technology readiness level and complications related to stowage, deployment, and support of the sail structure are both addressed by combining the University of Illinois-developed UltraSail and Cubesat expertise to design a small-scale solar sail deployment and propulsion experiment in low Earth orbit. The study analyzes multiple aspects of the problem from initial sizing and packaging of the solar sail film into two Cubesat-class spacecraft, through on-orbit deployment dynamics, attitude control of large and flexible space structure, and lastly predictions of performance and orbital maneuvering capability.

13:55 **AAS 09 - 418** **Cost Effectiveness of On-Orbit Servicing**
Tiffany Rexius, Jackson & Tull

This study was performed to model on-orbit servicing (OOS) of a pre-existing Low Earth Orbit and geostationary constellation. A conceptual model of each spacecraft was developed to determine mass and power allocation required based on the mission of thespacecraft. An OOS mass was added to the spacecraft which represented the mass of the components necessary to allow the spacecraft to be docked with. The servicing missions modeled were refueling, replacement of parts, and relocation. The driving factor of cost was sensitivity to OOS mass. For most constellations, OOS was not cost effective unless the OOS mass was very low.

14:20 **AAS 09 - 419** **Long-Term Stability Of Flower Constellations Under Planetary Oblateness**
Troy A. Henderson and Martin Avendano, Texas A&M University

A study of planetary oblateness on the stability of Flower Constellations is presented. The result is an investigation of station keeping requirements as well as a newly developed theory of FC design taking into account the perturbation.

14:45 **AAS 09 - 421** **New Color Visualization for Satellite Constellation**
P. J. Cefola, Consultant in Aerospace Systems; Z. J. Folcik, MIT Lincoln Laboratory; J. E. Draim, Consultant

This paper introduces a new color visualization of the coverage characteristics of a multiple satellite constellation. Each of the generated plots gives color-coded coverage information vs. user earth-fixed latitude and longitude.

15:10 **Break**

15:35 **AAS 09 - 422** **The Determination of Time-Variable Gravity From a Constellation of Non-Dedicated Satellites**

B.C. Gunter, P. Ditmar, and J. Encarnacao, Delft University of Technology

This study will assess the feasibility of using a constellation of non-dedicated satellites to determine the Earth's time-variable gravity field. Precise orbit data from the FORMOSAT-3/COSMIC satellite constellation will be processed and the results willbe compared to theoretical predications. The constellation should be able to provide information about the large scale (> 1000 km), high frequency (< 1 month) variations in the gravity field. The potential to accurately determine quantities such as J2(related to the Earth's oblateness) is valuable not only for Earth observation, but also for topics in mission design and orbit determination.

16:00 **AAS 09 - 423** **Numerical Computation of Optimal Electrodynamic Orbit Transfers**

Paul Williams, Delft University

Electrodynamic tether systems have the potential for allowing orbital maneuvers to be undertaken with little or no propellant. However, when operated in this mode, the current must be modulated on a fast timescale compared to the variation in the averageorbital elements. This paper introduces a new numerical technique for calculating optimal trajectories for general dynamical systems where the dynamics evolve on multiple timescales. The method is applied to the problem of determining optimal trajectories for electrodynamic tethers.

Session 18: Trajectory Optimization III

Chair: Dr. David Spencer, Penn State University

08:00 **AAS 09 - 424** **An Assessment of Multiple Satellite-Aided Capture at Jupiter**
Alfred Lynam , Kevin Kloster, and James Longuski, Purdue University

Satellite-aided capture is a mission design concept used to reduce the delta-v required to capture into a planetary orbit. The technique employs close flybys of a massive moon to reduce the energy of the planet-centered orbit. A sequence of close flybys of two or more of the Galilean moons of Jupiter may decrease the delta-v cost of Jupiter orbit insertion. A Ganymede-Io sequence saves 207 m/s of delta-v over a single Io flyby. These novel sequences have potential to benefit both NASA's Jupiter Europa orbiter mission and ESA's Jupiter Ganymede orbiter mission.

08:25 **AAS 09 - 429** **Autonomous Multi-Rover Trajectory Planning Using Optimal Control Techniques**
Michael A. Hurni, Pooya Sekhavat, and I. Michael Ross, Naval Postgraduate School

Future manned and robotic space missions call for autonomous coordination and control of planetary rovers. This paper presents the implementation of a pseudospectral (PS) optimal control-based algorithm for autonomous trajectory planning and control of several unmanned ground vehicles (UGV) with real-time information updates. The mission of the UGVs is to traverse from their initial start points and reach their targets in minimum time, with maximum robustness, while avoiding obstacles (static and dynamic) and each other. Control solutions are repeatedly recomputed and updated throughout the vehicles' missions. Simulation results illustrate the performance of the planner in various multi-vehicle scenarios.

08:50 **AAS 09 - 426** **An Optimal Initial Guess Generator For Entry Interface Targeters**
Juan S. Senent, Odyssey Space Research

If a pure numerical iterative approach is used, targeting entry interface (EI) conditions for nominal and abort return trajectories or for correction maneuvers can be computationally expensive. This paper describes an algorithm to obtain an optimal impulsive maneuver that generates a trajectory satisfying a set of EI targets: inequality constraints on longitude, latitude and azimuth and a fixed flight-path angle. Most of the calculations require no iterations, making it suitable for real-time applications or large trade studies. This algorithm has been used to generate initial guesses for abort trajectories during Earth-Moon transfers.

09:15 **AAS 09 - 427** **Constrained Optimal Orbit Design for Earth Observation Satellites Based on User Requirements**
Sharon Vtipil and Brett Newman, Old Dominion University

The purpose of this paper is to show that the user requirements for a satellite observation mission can be used to determine a constrained optimal orbit based on observation requests and sensor characteristics.

09:40 **Break**

10:05 **AAS 09 - 428** **Broad Search and Optimization of Solar Electric Propulsion Trajectories to Uranus and Neptune**

Damon Landau, Try Lam, and Nathan Strange, Jet Propulsion Laboratory

A procedure to produce a large variety of potential trajectories to Uranus and Neptune is discussed. A small set of exceptional trajectories emerges from this broad search and expand the range of missions available to these planets. The combination of solar electric propulsion (SEP) and assorted gravity assists would enable greater performance compared to chemical propulsion with many gravity assists or SEP with a single gravity assist. Variation in performance for different launch vehicles, SEP systems, and flight times is addressed.

10:30 **AAS 09 - 431** **Design of Guidance Laws for Lunar Pinpoint Soft Landing**

Jian Guo, Technical University of Delft; Congying Han, University of Surrey

Future lunar missions ask for the capability to perform precise Guidance, Navigation and Control (GNC) to the selected landing sites on the lunar surface. This paper studies the guidance issues for the lunar pinpoint soft landing problem. The primary contribution is the design of descent guidance laws based on the Pontryagin maximum principle and on interval analysis, respectively. The simulation shows that polynomial guidance law can achieve reasonable pinpoint landing accuracy at hundred-meters level, while the guidance law based on interval analysis is superior to the polynomial guidance law, in terms of robustness and achieving fine pinpoint soft landing.

Session 19: Planetary, Asteroid, and Deep Space Missions II

Chair: Yanping Guo, APL

08:25 **AAS 09 - 432** **Mission Design of Guided Aero-Gravity Assist Trajectories at Titan**
Jordi Casoliva and Daniel T. Lyons, Jet Propulsion Laboratory

The objective of this paper is to apply our recently developed aero-gravity assist guidance algorithm1 to Titan, in order to enable missions to the moons of Saturn by reducing propellant mass. This new approach represents a possible major breakthrough inour ability to target moons such as Enceladus. Although our guidance algorithm has been developed for high lift-to-drag (L/D) vehicles operating at Mars and Venus, it will be adapted to accommodate lower L/D vehicles operating in the Titan atmosphere.

08:50 **AAS 09 - 433** **Spacecraft Trajectory Design for Tours of Multiple Small Bodies**
Brent William Barbee, George Davis, and Sun-Hur Diaz, Emergent Space Technologies, Inc.

Spacecraft science missions to small bodies (asteroids and comets) have historically visited only one or several small bodies per mission. Our research goal is to create a trajectory design algorithm that generates trajectory sets allowing a spacecraft tovisit a significant number of asteroids during a single mission. There are several hundred thousand known asteroids, and this huge search space makes identifying optimal or feasible asteroid itineraries an NP-complete combinatorial minimization problem.An algorithm has been developed to traverse the search space and generate solutions, enabling trajectory design for multiple small body tours using available spacecraft propulsion technology.

09:15 **AAS 09 - 434** **Repeated Shadow Track Orbits for Space-SunSetter Missions**
Ahmed Gad and Ossama Abdelkhalik, Michigan Technological University

This paper introduces a new set of orbits, the “Repeat Shadow Track Orbits” (RSTO) in which the shadow of a spacecraft on Earth visits the same locations periodically every desired number of days. The J2 perturbation is utilized to synchronize the spacecraft shadow motion with both the Earth rotational motion and the Earth-Sun vector rotation. The general mathematical model to design an RSTO is presented. RSTOs' conditions are formulated and numerically solved. Results show the feasibility of RSTOs. An optimization process is developed to maximize the shadow duration over a given site. A Genetic Algorithm technique is implemented for optimization.

09:40 **Break**

10:05 **AAS 09 - 435** **Leveraging Flybys of Low Mass Moons to Enable an Enceladus Orbiter**
Nathan Strange, Jet Propulsion Laboratory; Stefano Campagnola,University of Southern California; and Ryan Russell, Georgia Institute of Technology

As a result of discoveries made by the Cassini spacecraft, Saturn’s moon Enceladus has emerged as a high science-value target for a future orbiter mission. However, a 2007 NASA study of an Enceladus orbiter mission found that entering Enceladus orbit either requires a prohibitively large orbit insertion ∆V (> 3.5 km/s) or a prohibitively long flight time (missions > 14 years). In order to reach Enceladus with a reasonable flight time and Delta-V budget, a new tour design method is presented thatuses gravity-assists of low-mass moons combined with v-infinity leveraging maneuvers. This new method can achieve Enceladus orbit with a leveraging + insertion ∆V of 1-1.5 km/s and a total mission duration less than the 14 year qualified lifetime of available radioisotope power systems.

10:30 AAS 09 - 436 On the Orbit Selection of the Space Solar Telescope ADAHELI

F. Curti and G. Russo, University of Rome "Sapienza"; F. Longo, Italian Space Agency

ADAHELI (ADvanced Astronomy for HELIophysics) is a project of the Italian Space Agency to carry out a small mission on the investigation of solar photospheric and chromospheric dynamics, via high-resolution spectro-polarimetric observations in the near-infrared spectral range. The present study deals with the orbit selection in order to satisfy the payloads' requirements. The main driver, in searching the suitable orbit, is the doppler shift that affects the orbiting telescope. The total amount of the doppler shift shall be less than 4 km/s with the objective of having 2 km/s for as long as possible. Three classes of orbits are analyzed: Sun-Synchronous Circular Orbits, Sun-Synchronous Frozen Elliptical Orbits and Frozen Elliptical Orbits.

10:55 AAS 09 - 437 Orbit Determination and Lunar Gravity Field Estimation Results of SELENE (KAGUYA)

Hitoshi Ikeda, Mina Ogawa, Masao Hirota, Shigehiro Mori, and Takahiro Iwata, Japan Aerospace Exploration Agency; Chiaki Aoshima, Takafumi Ohnishi, and Shiro Ishibashi, Fujitsu Ltd.; Hirotomo Noda and Yoshiaki Ishihara, National Astronomical Observatory ofJapan; Noriyuki Namiki, Kyushu University

SELENE (Kaguya) is Japan's first large lunar explorer aims to obtain the scientific data to investigate the origin and the evolution of the Moon and to acquire engineering techniques for the future Moon explo-ration and utilization. The SELENE mission consists of three satellites: the main orbiter (Kaguya), the relay sub-satellite (Okina), and the VLBI sub-satellite (Ouna). The paper describe the results of the orbit determination of these spacecrafts from the nominal mission phase to the extended missionphase. In addi-tion, the collision analysis for Kaguya and Okina, the present status of lunar gravity field estimation re-sults is also described.

Session 20: Orbital Dynamics II

Chair: Dr. Felix Hoots, The Aerospace Corporation

08:00 **AAS 09 - 438** **Optimal Low-Energy Transfers in the Concentric Circular Restricted Four-Body Problem**
Fady M. Morcos, Cesar A. Ocampo, The University of Texas at Austin

The problem of transfer in the Concentric Circular Restricted Four-Body problem is considered in this paper. The mission is broken down into segments in two separate three-body systems, which are later patched together to complete the transfer; similar tothe patched conics technique utilized in the relative two-body problem. The invariant stable/unstable manifold structure of the collinear equilibrium points forms networks of trajectories, serving as low energy passageways. Intersections between those tubes provide the framework for designing the transfer. The necessary conditions for local optimality of the transfer are verified with Primer Vector Theory.

08:25 **AAS 09 - 439** **Ballistic Coefficient and Density Estimation**
Craig A. McLaughlin and Andrew Hiatt, University of Kansas

Atmospheric density modeling is the greatest uncertainty in the dynamics of low Earth satellite orbits. This paper examines the effects of ballistic coefficient errors in using precision orbits to estimate total density along the satellite orbit. The density is estimated using Challenging Minisatellite Payload (CHAMP) precision orbit data. The accuracy of the precision orbit derived density is compared to CHAMP accelerometer derived density with various values of initial ballistic coefficient. The paper examines the ability of the estimation process to estimate ballistic coefficient in the presence of errors in the initial guess for ballistic coefficient.

08:50 **AAS 09 - 440** **Mean Element Propagations Using Numerical Averaging**
Todd Ely, Jet Propulsion Laboratory

The long-term evolution characteristics (and stability) of an orbit are best characterized using a mean element propagation of the perturbed two body variational equations of motion. The averaging process eliminates short period terms leaving only secular and long period effects. In this study, a non-traditional approach is taken that averages the variational equations using adaptive numerical techniques and then numerically integrating the resulting EOMs. Doing this avoids the Fourier series expansions and truncations required by the traditional analytic methods. The resultant numerical techniques can be easily adapted to propagations at most solar system bodies.

09:15 **AAS 09 - 441** **Arbitrary Order Vector Reversion of Series and Implicit Function Theorem**
James D. Turner, Manoranjan Majji, and John L. Junkins, Texas A&M University,

The increasing challenges posed by complex missions and nonlinear system behaviors force analysts to investigate the use of high-order modeling and optimization methods for handling challenging applications. Two types of calculations are of significancefor addressing these challenges: (1) successive approximation techniques, and (2) implicit function theorem calculations. Regardless of the methods analyst must deal with derivative calculations for implicit functions.

09:40 **Break**

10:05 **AAS 09 - 442** **Earth Moon Trajectory Design Using Lagrange Implicit Function Theorem**
Majji, M., Junkins, J. L. and Turner, J. D., Texas A&M University, College Station, TX

A generalization of the Lagrange implicit function theorem is applied to obtain approximate neighboring solutions to the Earth-moon trajectory design problem. It is shown that, in the practical event of small deviations from the optimal solution, differential correction impulses can be calculated a-priori by making judicious use of the approximate solutions obtained from the high order implicit function derivatives. Sensitivities of the departure motion dynamics with respect to parameters of the boundaryvalue problem are obtained as a by-product of the calculations involved. Determination of differential corrections based on a linear uncertainty analysis of the perturbed motion is demonstrated.

10:30 **AAS 09 - 443** **Low-Energy Ballistic Transfers to Lunar Halo Orbits**
Jeffrey S. Parker, Jet Propulsion Laboratory

Recent lunar missions have begun to take advantage of the benefits of low-energy ballistic transfers between the Earth and the Moon rather than implementing conventional Hohmann-like transfers. Both Artemis and GRAIL will be implementing low-energy lunartransfers in the next few years. This paper explores the characteristics and potential applications of new families of low-energy ballistic lunar transfers. The transfers presented here begin from a wide variety of different orbits at the Earth and followseveral different distinct pathways to the Moon. This paper characterizes these pathways to identify desirable low-energy transfers for future lunar missions.

10:55 **AAS 09 - 444** **State Transition Matrix Approximation Using a Generalized Averaging Method**
Yuichi Tsuda, Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency; Daniel J. Scheeres ,The University of Colorado

This paper presents a method for approximating the state transition matrix for orbits around a primary body and subject to arbitrary perturbations. A generalized averaging method is employed to construct a functional form of the approximate state transition matrix composed only of elementary analytic function and capable of capturing the symplectic structure precisely. The resulting matrix is expressed with a small number of parameter matrices and osculating orbit parameters at an initial epoch. This method has been developed for implementation onboard spacecraft for high accuracy formation flying missions. The theoretical background and some numerical evaluations are shown in the paper.

RECORD OF MEETING EXPENSES

AAS/AIAA Astrodynamics Specialist Conference
Renaissance Pittsburgh Hotel, Pittsburgh, Pennsylvania
9-13 August 2009

Name:______________________________ Organization: ______________________________

Category	Early Registration (through 1 Aug 2009)	Late Registration
Full - AAS or AIAA Member	$450	$500
Full - Non-member	$535	$585
Retired*	$130	$180
Student*	$130	$180

Registration Fee: ____________________

Conference Proceedings (Hard Cover)[1] ___ @ $240 ____________________

Early Bird Reception Guest Ticket ___@ $50 ____________________

Award Banquet Guest Ticket ___@ $50 ____________________

TOTAL: ____________________

Recorded by: ________________________________

[1] [1] Digital Proceedings on Compact Disk (CD) are provided after conference at no extra cost

CONFERENCE PLANNER

Monday 10 August											
Session	Symphony Room	8am	8:25	8:50	9:15	9:40	10:05	10:30	10:55	11:20	
1	A	09-301	09-302	09-303	09-304	Break	09-305	09-306	09-307	09-308	
2	B	09-309	09-310	09-311	09-312	Break	09-313	09-314	09-315		
3	C	09-316	09-317	09-318	09-319	Break	09-320	09-321	09-322		
		1:30 pm	1:55	2:20	2:45	3:10	3:35	4:00	4:25	4:50	5:15
4	A	09-328	09-323	09-325	09-324	Break	09-327	09-326	09-330	09-329	09-331
5	B	09-332	09-333	09-334	09-335	Break	09-337	09-338	09-339		
6	C	09-340	09-341	09-342	09-343	Break	09-344	09-345	09-346	09-347	
Tuesday 11 August											
Session	Symphony Room	8am	8:25	8:50	9:15	9:40	10:05	10:30	10:55	11:20	
7	A		09-348	09-349	09-350	Break	09-351	09-352			
8	B	09-354	09-357	09-353	09-359	Break	09-356	09-355	09-358		
9	C	09-360	09-361	09-362	09-363	Break	09-364	09-365	09-366	09-367	
		1:30 pm	1:55	2:20	2:45	3:10	3:35	4:00	4:25	4:50	5:15
10	A	09-368	09-369	09-370	09-371	Break	09-372	09-373	09-374	09-375	
11	B	09-376	09-377	09-378	09-379	Break	09-380	09-381	09-382		
Wednesday 12 August											
Session	Symphony Room	8am	8:25	8:50	9:15	9:40	10:05	10:30	10:55	11:20	
12	A		09-383	09-384	09-385	Break	09-386	09-387	09-388		
13	B	09-389	09-390	09-391	09-392	Break	09-393	09-420	09-394		
14	C	09-395	09-396	09-397	09-398	Break	09-399	09-400	09-402		
		1:30 pm	1:55	2:20	2:45	3:10	3:35	4:00	4:25	4:50	5:15
15	A	09-403	09-404	09-405	09-406	Break	09-407	09-408	09-425		
16	B	09-409	09-410	09-411	09-412	Break	09-413	09-414	09-415	09-416	
17	C	09-417	09-418	09-419	09-421	Break	09-422	09-423			
Thursday 13 August											
Session	Symphony Room	8am	8:25	8:50	9:15	9:40	10:05	10:30	10:55	11:20	
18	A	09-424	09-429	09-426	09-427	Break	09-428	09-431			
19	B		09-432	09-433	09-434	Break	09-435	09-436	09-437		
20	C	09-438	09-439	09-440	09-441	Break	09-442	09-443	09-444		

AUTHOR INDEX