



2017

Interplanetary Small Satellite Conference

beyond LEO

Conference Program

Small satellite developments in:

Science Goals and Instrumentation
Interplanetary Missions, Systems, and Architectures
Challenges of Small Satellites for Interplanetary Applications
Proposed Spacecraft Subsystems and Technologies
Management, Systems Engineering, Policy and Cost



Hosted by:

San José State University
San Jose, CA
May 1-2, 2017

www.intersmallsatconference.org

Monday, May 1, 2017

Time	Event
8:00-8:45	Registration
8:45-9:40	Keynote Speaker: Jason Crusan
9:40-10:00	Coffee Break
10:00-11:30	Session A: EM-1 Missions <i>Session chairs: A. Babuscia and F. Alibay</i>
	A.1 Lunar Ice Cube Mission Progresses and Challenges (P. Clark)
	A.2 Lunar Flashlight (J. Baker)
	A.3 NEA Scout (J. Baker)
	A.4 To the Moon in a Shoebox: Engineering the Lunar Polar Hydrogen Mapper (S. West)
	A.5 BioSentinel – A Deep Space Radiation BioSensor Mission (R. Hanel)
	A.6 NASA's CubeQuest Awards Prizes to Citizens Demonstrating Advanced CubeSat Capabilities Useful for Deep Space Science Missions (J. Cockrell)
11:30-12:00	Session A Q&A Panel
12:00-13:00	Lunch
13:00-14:15	Session B: Telecommunication Challenges <i>Session chairs: B. Malphrus and D. Abraham</i>
	B.1 CubeSat Telecom System Needs for Deep-Space Missions (M. Kobayashi)
	B.2 Inflatable Antenna for CubeSat at X-Band: Results of the Experimental Tests (A. Babuscia)
	B.3 MarCO Telecom System Design (M. Kobayashi)
	B.4 Development of Telecommunications Systems for EM-1 Interplanetary CubeSat Missions (K. Angkasa)
	B.5 Integrated Communications Antennas and Solar Arrays for Interplanetary CubeSats (A. Choudhari)
14:15-14:40	Session B Q&A Panel
14:40-15:00	Coffee Break

Monday, May 1, 2017 (continued)

Time	Event
15:00-16:00	Session C: Ground Support <i>Session chairs: K. Angkasa and D. Dalle</i>
	C.1 Progress Toward Simultaneous Communications with Multiple SmallSats via a Single Antenna (D. Abraham)
	C.2 Enabling University-Operated Ground Support for Deep Space Small Spacecraft Missions—A Pilot Development with the Morehead State University 21 m Ground Station (J. Kruth)
	C.3 Enabling Deep Space Small Satellite Missions Using NASA AMMOS Products and Services (E. Basilio)
	C.4 End-to-End System with Multi-Mission Systems (P. Di Pasquale)
16:00-16:25	Session C Q&A Panel
16:25-16:40	Coffee Break
16:40-17:25	Session D: Trajectory, Propulsion, and Launch <i>Session chairs: J. Thanga and A. Babuscia</i>
	D.1 Economical Mars Transits Outside the 26 Month Hohman Transfer Window (D. Taylor)
	D.2 Interorbital Systems: Launch Services to LEO, LUNA, and Beyond (R. Milliron)
	D.3 Solar Thermal Propulsion for Interplanetary Small Satellites (S. Rabade)
17:25-17:50	Session D Q&A Panel
18:00-19:30	Dinner and Social

Tuesday, May 2, 2017

Time	Event
8:00-8:45	Registration
8:45-9:40	Keynote Speaker: Sharmila Bhattacharya
9:40-10:00	Coffee Break

Tuesday, May 2, 2017 (continued)

Time	Event
10:00-11:45	Session E: Mission Concepts <i>Session chairs: P. Clark and A. Babuscia</i>
	E.1 SunRISE: Sun Radio Interferometer Space Experiment (<i>F. Alibay</i>)
	E.2 Morph (<i>S. Matousek</i>)
	E.3 Small Asteroid Impactor in Near Trans-lunar Space (SAINTS) (<i>G. Gyuk</i>)
	E.4 Spacecraft Penetrator for Increasing Knowledge of NEOs (SPIKE) (<i>E. Asphaug</i>)
	E.5 SunCube FemotSats: A New Tool in the Interplanetary Exploration Toolbox (<i>J. Thanga</i>)
	E.6 Detailing Small-Body Surface Properties with the Asteroid Mobile Imager and Geologic Observer (AMIGO) (<i>S. Schwartz</i>)
	E.7 ATROMOS: Using Nano-Satellite Technology to Explore the Mars Surface (<i>M. Murbach</i>)
11:45-12:15	Session E Q&A Panel
12:15-13:15	Lunch
13:15-14:45	Session F: Autonomy, Pointing, and EDL <i>Session chairs: A. Chandra and F. Alibay</i>
	F.1 Use of Shape Memory Alloy Actuators for Precise Pointing on Interplanetary Small Satellites and CubeSats (<i>N. Sonawane</i>)
	F.2 Autonomous Surface Mobility on Small Solar System Bodies with Hopping/Tubling Rovers (<i>B. Hockman</i>)
	F.3 Inflatable Entry, Descent, and Landing System for CubeSats (<i>M. Herrera</i>)
	F.4 Radiometric Actuators for CubeSat Attitude Control in Deep Space: A Comparison between Analytical and Computational Models (<i>R. Nallapu</i>)
	F.5 Liquid Reaction Wheel Based on MHD Effect in Liquid Mercury (<i>G. Veshapidze</i>)
	F.6 How Small Is a Small Spacecraft? Size Versus Autonomy in Planetary Spacecraft (<i>F. Crary</i>)
14:45-15:15	Session F Q&A Panel

Tuesday, May 2, 2017 (continued)

Time	Event
15:15-15:35	Coffee Break
15:35-17:05	Session G: Bus Technologies (NASA CubeQuest and Other Interplanetary CubeSat Concepts) <i>Session chairs: J. Cockrell and D. Dalle</i>
	G.1 Expandable Hybrid Computing Platforms for SmallSats (<i>K. Conway</i>)
	G.2 Analysis and Design of Small 6U CubeSat For Future Space Exploration Missions (<i>M. Rahman</i>)
	G.3 Effective CubeSat Fault Management Strategies Beyond Low Earth Orbit (<i>M. Sorgenfrei</i>)
	G.4 Saberwing: An Interplanetary SmallSat Technology Demonstration (<i>J. Pate</i>)
	G.5 Managing Thermal Requirements of a CubeSat System (<i>S. Pierce</i>)
	G.6 Flexible Flight Software Framework Facilitating Evolving Devices and Interfaces (<i>D. Forman</i>)
17:05-17:35	Session G Q&A Panel
17:35-17:40	Closing Remarks

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1. Welcome

Welcome to the fifth Interplanetary Small Satellite Conference, which will address the technical challenges, opportunities, and practicalities of space exploration with small satellites.

The conference is organized by an evolving group of students, engineers, and researchers and can trace its roots back to the iCubeSat 2012 conference. The scope of the conference is slightly broader and includes interplanetary small satellite missions that do not fit into the CubeSat standard. We believe that with this shift we will be able to incorporate an important segment of the community as well as encourage the “outside the box” thinking that will be critical to future interplanetary small satellite missions.

Thank you for joining us in San Jose.

—*The Organizing Committee*

2. Contacts and Hours

The registration desk will be open from 8:00 am on May 1 and from 8:00 am to 3:00 pm on May 2. Please don't hesitate to contact the organizing committee at info@intersmallsatconference.org at any time during the conference.

3. Organizing Committee



Alessandra Babuscia received her B.S. and M.S degrees from the Politecnico di Milano, Milan, Italy, in 2005 and 2007, respectively, and her Ph.D. degree from the Massachusetts Institute of Technology (MIT), Cambridge, in 2012. She is currently a Telecommunication Engineer at NASA JPL (337G). She has developed communication systems for different university missions (CASTOR, ExoplanetSat, Ter-Sat, REXIS, TALARIS). She has been with the Communication Architecture Research Group, NASA Jet Propulsion Laboratory, Pasadena, CA. Her current research interests include commu-

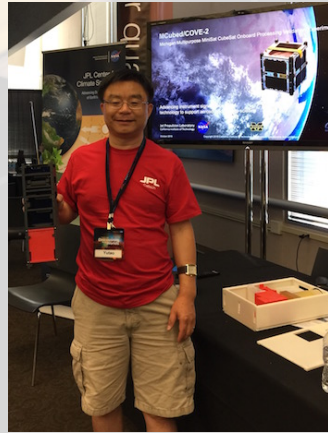
nication architecture design, statistical risk estimation, multidisciplinary design optimization, and mission scheduling and planning. She was a member of the organizing committee for iCubeSat 2012 (MIT, Cambridge), and she is a session chair at the IEEE Aerospace Conference.

Travis Imken received an M.S. in Aerospace Engineering from The University of Texas at Austin in 2014. His research focused on the development of the 3D-printed cold-gas attitude control system for the JPL INSPIRE CubeSatellites. While at UT Austin, Travis worked in the Texas Spacecraft Laboratory and supported many small satellite missions in various leadership roles, including the Bevo-1 picosatellite and the Bevo-2, ARMADILLO, and RACE CubeSats. He currently works as a Systems Engineer in the Advanced Design Engineering Group at the Jet Propulsion Laboratory. Travis serves as a systems engineer and model developer for the Team Xc concurrent design team. He also works as a systems engineer for the proposed interplanetary Lunar Flashlight and NEA Scout CubeSat missions. Travis is an avid skier and enjoys the outdoors.



Farah Alibay received her Bachelor's and Master's degrees from the University of Cambridge in Aerospace and Aerothermal Engineering in 2010, and her PhD in Space Systems Engineering from the Massachusetts Institute of Technology (MIT) in 2014. Her PhD research focused on the use of spatially and temporally distributed systems for the exploration of planetary bodies in the solar system, as well as developing tools for the rapid evaluation of mission concepts in early formulation. She is currently working as a systems engineer at NASA's Jet Propulsion Laboratory (JPL) in the Planetary Mission Formulation group.

Yutao He Yutao He is currently a Senior Technologist in the Advanced Computer Systems and Technologies group at NASA Jet Propulsion Laboratory (JPL), leading researches in developing advanced avionics technology for future spacecraft. He received his B.E. in Electrical Engineering from Tsinghua University in Beijing, China and his Ph.D. in Computer Science from UCLA. His current research interests are rad-hard SmallSat/CubeSat avionics for deep space missions, FPGA-based reconfigurable computing, advanced fault-tolerant avionics architecture, real-time embedded systems, and systems engineering of complex systems design. He is the C&DH Lead for interplanetary Lunar Flashlight and NEA Scout CubeSat missions. He is also a visiting faculty member at UCLA and CSULA, teaching undergraduate/graduate courses in Electrical Engineering and Computer Science.



Carlyn Lee is a software engineer for the Telecommunication Architecture Group at NASA Jet Propulsion Laboratory. She is involved in link budget analysis tools development and optimization for space communication and navigation. Her research interests include communication systems, networking architecture, and high-performance computations. She received her B.S. and M.S. degrees in computer science

from the California State University, Fullerton in 2011 and 2012.

Derek Dalle is an aerodynamics engineer in NASA Ames' Computational Aerosciences branch (Code TNA) with Science & Technology Corp. His current focus is aerodynamics for the Space Launch System using NASA's High-End Computing Capability efficiently. He received a Ph.D. from Michigan in 2013. His interests include various types of trans-atmospheric vehicles including air-breathing hypersonic engines, launch vehicles, reentry applications, and others. Currently he is also involved in low-boom commercial supersonic transport research and development.



Rodrigo Zeledon received his B.S. in Aerospace Engineering from the Massachusetts Institute of Technology in 2009. He is currently a fourth-year Ph.D. student at Cornell University's Space Systems Design Studio. His research interests include spacecraft dynamics, small spacecraft design and small-scale propulsion systems. His current work involves the development of an electrolysis propulsion system for CubeSats.



Aman Chandra received a B.E. in Chemical Engineering from M.S. Ramiah Institute of Technology, Bangalore, India in 2012 and an M.S. in Aerospace Engineering from Arizona State University's SpaceTReX in 2015. He has been working on NASA JPL's inflatable antenna project and is on the Engineering team for AOSAT 1 Cubesat Centrifuge mission and LunaH-Map lunar Cubesat mission. His interests include Space Systems Engineering, Structural Design, Finite Element Analysis, Multi-parameter Design Optimization and Statistical Risk Assessment.





Krisjani S. Angkasa Kris Angkasa is a Telecommunications Systems Engineer at the Jet Propulsion Laboratory. She started JPL in 1990 as a student, and since has made many contributions to the deep space missions including, Kepler, Mars Exploration Rover (MER), Mars Reconnaissance Orbiter (MRO), MAVEN, Juno, and Mars Science Laboratory (MSL). Her main focus is in the design, development, test, integration, and flight operations of the DSN ground & deep space radios. She spent two years at the Hughes Space &

Communications (now Boeing) as a Payload Communication Systems Lead for a Ka-Band commercial satellite that is currently used by DirectTV. She earned her B.S. in Computer Science from California Polytechnic University, Pomona and M.S. in Electrical Engineering from USC. Currently, she is the Telecommunications Systems Engineer for Lunar IceCube, a 6U cubesat slated for SLS EM-1 launch, and Mars 2020 Rover mission.

Julianna Fishman is the founder of Technology Horse LLC, a program and project management services company. Ms. Fishman facilitates activities of the Technology Integration Agent, a process utilized by several multidisciplinary NASA programs to define mission, program, and project priorities; support requirements analysis; and perform technology assessments. From 1994 to the present, she has provided program and project formulation and implementation support to several NASA programs at both NASA Headquarters and Ames Research Center to include: Space Biology, Gravitational Biology and Ecology, Fundamental Space Biology, Biomolecular Physics and Chemistry, Astrobiology Technology Group, Dust Management Project, Small Spacecraft Technology Program, Small Spacecraft Systems Virtual Institute, and the Office of the Center Chief Technologist. In her capacities, Ms. Fishman makes contributions in the areas of program and project document content development; focus group, workshop, and review planning; and development of presentations, white papers, and communications material. She holds a Bachelor of Science degree in biology and a Masters in Business Administration from Norwich University in Northfield, Vermont.



4. Location and Venue

The conference will take place at the San Jose State University Student Union. The address for the venue is 211 S 9th St, San Jose, CA 95112.



LEGEND

Electronic Door

- Wheelchair accessible
- Restricted access

Parking

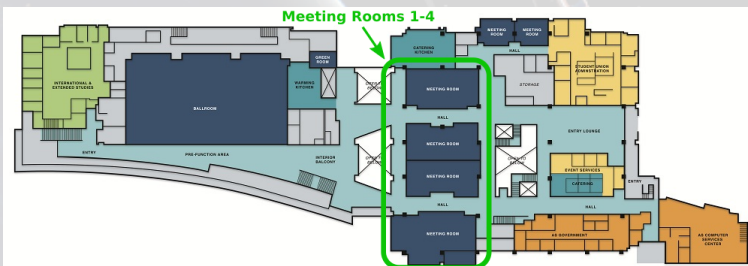
- Disabled parking DMV placard
- Disabled parking University permit
- 20/30 minutes

- Elevator
- Park and Ride shuttle

The keynote and other sessions will be in the indoor theater on the bottom floor of the student union. It is in the maroon square in the figure below, and the purple square highlights the lobby area of the theater where the registration, exhibition hall, and coffee breaks will be.



Lunch and dinner on May 1 will be in Meeting Room 4 on the upper level, while lunch on May 2 will be in Meeting Room 1, also on level 2. No conference events are scheduled for level 1. The meeting rooms are highlighted with a green square below, but the meeting rooms are not numbered.

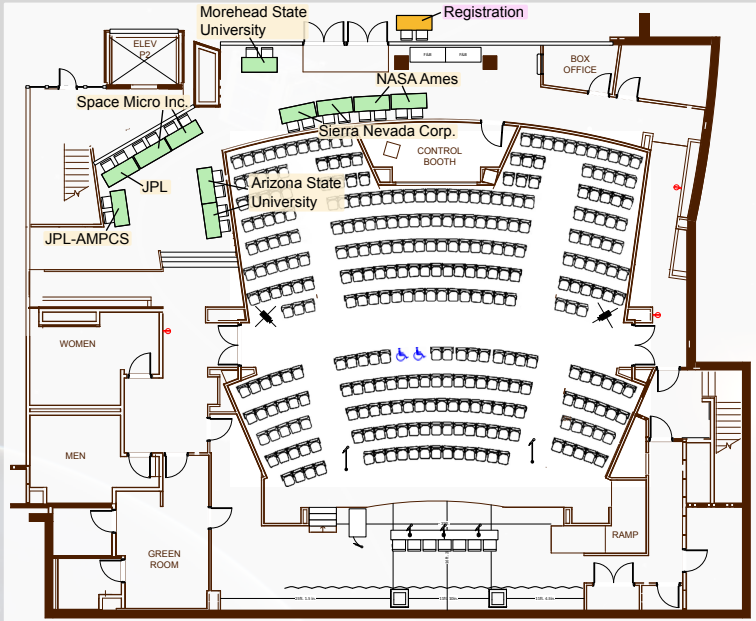


5. WiFi Access

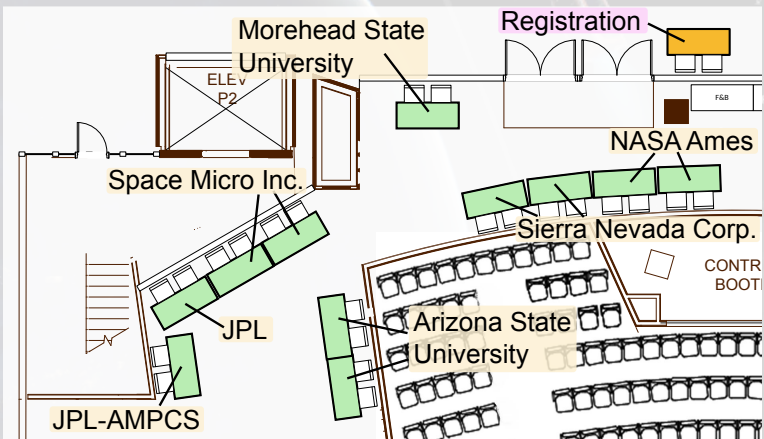
For wireless internet access, connect to the “SJSU_Guest” network. You will have to register to use the network; for more information see <http://its.sjsu.edu/resources/wifi-guides/wireless-guest/index.html>

6. Exhibitors and Lunch Area Map

A rough diagram of the theater and exhibitor area is shown below. We hope you enjoy interacting with our great sponsors and exhibitors this year!



A more detailed diagram of the exhibitor area is shown below.



7. Keynote Speaker Biographies

Jason Crusan (NASA Headquarters)

As director of the Advanced Exploration Systems (AES) Division within the Human Exploration and Operations Mission Directorate (HEOMD), Jason Crusan serves as NASAs senior executive, advisor and advocate on technology and innovation approaches leading to new flight and system capabilities for human exploration of space. He manages over 450 civil servant employees and 150 onsite contractors with an active portfolio of 20-30 technology, engineering and flight development projects. He leads integration with the agencies Space Technology Mission Directorate and programs within other HEOMD divisions including International Space Station and Exploration Systems Development.

Using an integrated approach that leverages public-private partnerships, industry, international parSharmila Battacharyatnrs, and academia, Mr. Crusan serves as the senior leader for AES across all NASA centers which involves: developing and maintaining critical human spaceflight capabilities; maturing new integrated systems, instruments, and ground systems; and delivering critical multi-million dollar flight hardware for NASA. He provides the executive management and leadership needed to develop effective technology development strategies, system acquisition strategies, contracting mechanisms, joint investment models and partnerships in short, he develops the innovative approaches needed to maximize NASAs access to new technologies and capabilities for human spaceflight.

Before becoming director of the agencies new Advanced Exploration Systems organization in 2012, Crusan fostered innovation at NASA in many key roles beginning in 2005. He served as chief technologist for space operations, and successfully directed various technical and strategic initiatives as program executive or project manager. He was part of the Miniature Radio Frequency Program (Mini-RF), which flew two radar instruments to the moon to map the lunar poles, search for water ice, and demonstrate future NASA communication technologies. Currently, he also serves as the Director of the Center of Excellence for Collaborative Innovation (CoECI) formed to advance the utilization of open innovation methodologies within the U.S. government.

Crusan holds bachelor's degrees in electrical engineering and physics, a masters degree in computer information systems, and is currently a candidate for a doctorate in Engineering Management at George Washington University. Mr. Crusan is married and has two children.



Sharmila Bhattacharya (NASA Ames Research Center)

Dr. Sharmila Bhattacharya is a senior scientist and Principal Investigator of the Biomodel Performance Laboratory in the Space Biosciences Division at NASA Ames Research Center in California. Prior to working at NASA, Sharmila Bhattacharya earned her



Masters and PhD degrees in Molecular Biology at Princeton University, followed by post-doctoral research in Neurobiology at Stanford University.

At NASA Ames Research Center, she served as the Lead Scientist to develop different biological habitats for the International Space Station. Sharmila also served as the Acting Project Manager for Small Biological Payloads flying on Progress, Soyuz and shuttle missions. Later Dr. Bhattacharya served as Chief Scientist for Astrobiology and the Small Spacecraft Division, helping integrate science payloads on a variety of space flight platforms including free-flyers and small satellites. Dr. Bhattacharya has served as the Principal Investigator for the first shuttle flight experiment that utilized fruit flies (Fly Immunity and Tumors, or FIT) to understand the effects of space flight on the immune system. She is the principal investigator or co-investigator for at least six other biology-related spaceflight missions that have flown or are scheduled to fly between 2014 and 2018. Some recent spaceflight experiments that she has been involved with include using biological models to understand the effects of space on the cardiovascular system, neurobehavioral system and pathogen virulence. A study that is of particular interest to interplanetary small satellites is “Biosentinel”, which uses yeast cells to understand the effects of radiation on DNA damage, and is being developed as a secondary payload to fly on platforms such as Exploration Mission 1 (EM-1). This payload and the associated hardware will be important in the context of future deep space missions.

8. Conference Abstracts

K.1 CubeSats: Enabling Technology Development and Broad Access to Space

Jason Crusan
(*NASA Headquarters*)

Today's small satellites will play an important part of future NASA exploration because of their potential to reduce the size and cost of complex space missions. In recent years, considerable advancements in miniaturized instruments and technology have increased the use of small satellites for operational applications, science experiments, larger missions, technology demonstrations, and engagement of educational organizations.

NASA plans to continue using CubeSats to enable agency goals to expand the frontiers of knowledge, capability, and opportunity in space; advance understanding of Earth; and improve the quality of life on our home planet. Current and emerging capabilities of these small spacecraft show great promise for furthering space-based exploration and scientific discovery, facilitating technology maturation, and providing opportunities for hands-on student flight research. CubeSats are a viable platform for communication relay, mission assistance, cameras, and navigation beacons for real time mission augmentation. This talk will outline how NASA utilizes small satellites to advance technology capabilities for application to upcoming human spaceflight activities in areas such as avionics, communications, operations and space biology.

K.2 Using “canaries in the coal mine” to prepare for long term human exploration of deep space

Sharmila Battacharya
(*NASA Ames Research Center*)

We are entering a new and exciting phase of space exploration. There is an increase in the opportunities to launch science experiments and cargo into space. There is wide-spread participation by commercial aerospace companies that are working with NASA to increase frequent access to space. Along with this endeavor comes the necessity to conduct research that helps understand the ramifications of long-term deep space exploration on biological systems. As no biological experiments have been conducted beyond low Earth orbit in over forty years since the Apollo era, there is an urgent need to develop the tools that are required to conduct such investigations.

Biosentinel is an excellent example of a compact, autonomous nanosatellite system that will carry a well-characterized biological organism on a lunar fly-by trajectory and into a heliocentric orbit. The experiment will measure the effect of highly ionizing deep space radiation particles on DNA damage and growth responses and compare them to identical controls on the ground and on the International Space Station. This biosensor system will be supported by data from a miniature LET spectrometer instrument and from other fabricated components including microfluidic cards, fluid delivery systems, thermal control for each of the 18 independent microfluidic cards, 3 color optical measurements to monitor growth and health of the cells and communication systems that will allow the data to be transmitted from the space craft to Earth. Several considerations are important for planning such a mission that include a four to six month pre-launch waiting period and then a six month to a one year flight duration.

It is important to use well-characterized biological model systems to understand the effects of this novel environment in parallel with efforts to build the equipment that will ultimately take humans in to deep space. Understanding the physiological effects of the highly ionizing and damaging radiation while traveling for long durations in a microgravity environment will not only be interesting, but essential to the efforts of optimizing deep space travel for humans.

A.1 Lunar Ice Cube Mission Progress and Challenges

Pamela Clark, Jonathan Sauder (*JPL/Caltech*)
Aman Chandra, Jekan Thangavelautham (*Arizona State University*),
and
Benjamin Malphrus (*Morehead State University*)

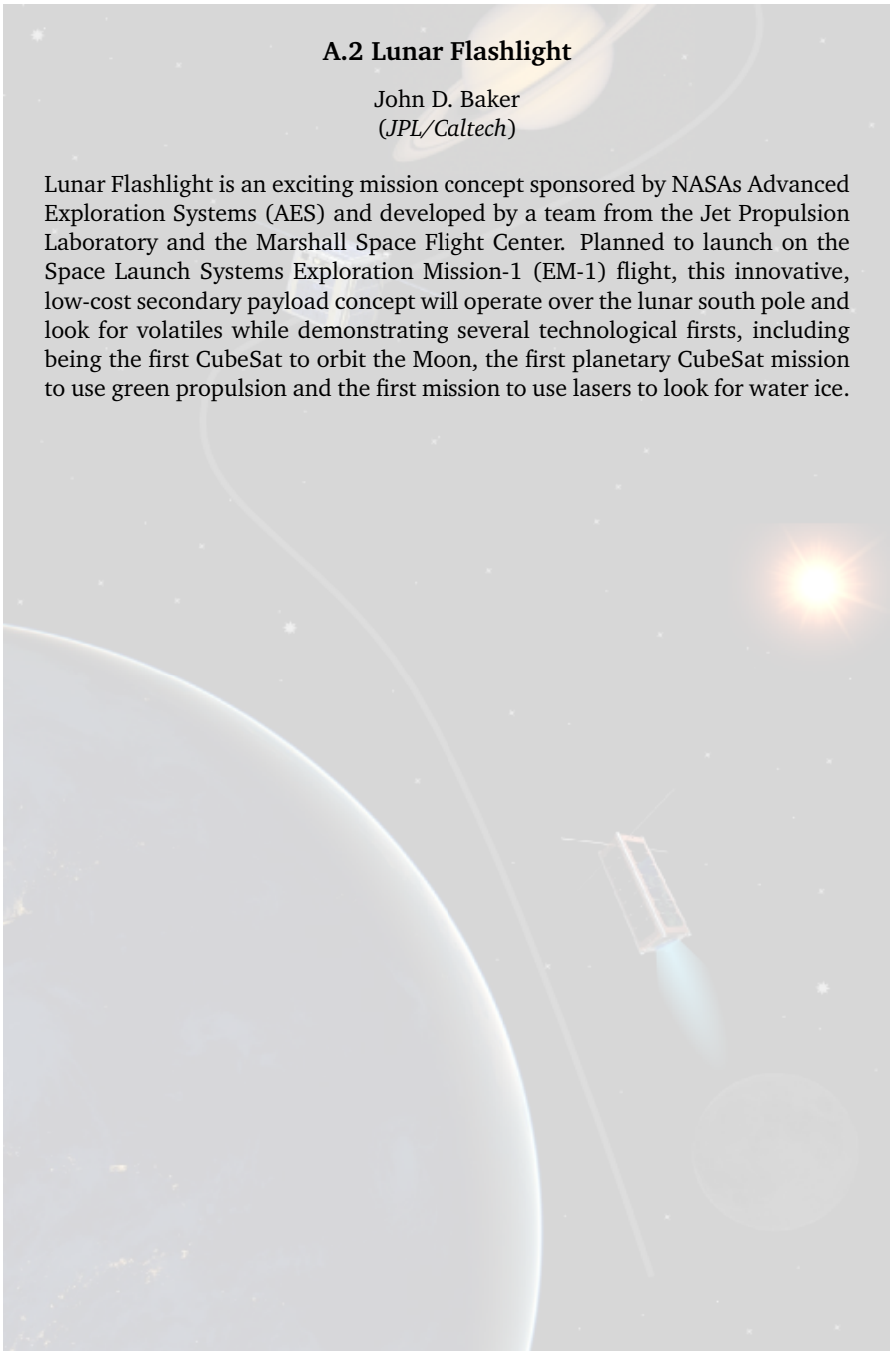
Interplanetary CubeSats and small satellites can provide means to explore space and to perform science in a more affordable way. However, the telecommunication systems currently implemented on CubeSats will need to improve to support interplanetary missions. One of the area of concern is the antenna. Hence, a possible solution is to develop inflatable antennas which can be packaged efficiently, occupying a small amount of space, and they can provide, once deployed, large dish dimension and correspondent gain. A prototype of a 1 m inflatable antenna for X-Band has been developed in a joint effort between JPL and ASU. The design is based on a spherical inflatable membrane that allows reaching a more stable inflatable surface, hence improving the electromagnetic performance. The antenna was fabricated, and tested at the anechoic chamber of Morehead State University in Kentucky. This presentation will detail the principle challenges in developing the new antenna and the results of the experimental tests.

Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

A.2 Lunar Flashlight

John D. Baker
(*JPL/Caltech*)

Lunar Flashlight is an exciting mission concept sponsored by NASA's Advanced Exploration Systems (AES) and developed by a team from the Jet Propulsion Laboratory and the Marshall Space Flight Center. Planned to launch on the Space Launch Systems Exploration Mission-1 (EM-1) flight, this innovative, low-cost secondary payload concept will operate over the lunar south pole and look for volatiles while demonstrating several technological firsts, including being the first CubeSat to orbit the Moon, the first planetary CubeSat mission to use green propulsion and the first mission to use lasers to look for water ice.



A.3 NEA Scout

John D. Baker
(JPL/Caltech)

NEA Scout is a mission that was selected by NASA's Advanced Exploration Systems (AES) and is being developed by a team from the Marshall Space Flight Center and the Jet Propulsion Laboratory. This innovative, low-cost concept will map an asteroid and demonstrate several technological firsts, including being the first CubeSat to reach an asteroid. Before sending astronauts to any new space environments, it is important to send robotic scouts to survey the destination and learn about the risks and challenges they may pose to future human explorers. Near-Earth Asteroid Scout, or NEA Scout, will perform reconnaissance of an asteroid using a CubeSat and solar sail propulsion, which offers navigation agility during cruise for approaching the target. Propelled by sunlight, NEA Scout will flyby and observe a small asteroid (<300 feet in diameter), taking pictures and observing its position in space, the asteroid's shape, rotational properties, spectral class, local dust and debris field, regional morphology and regolith properties. NEA Scout's observations will directly assist in retiring the unknowns related to human exploration of asteroids and planetary small bodies. The data collected will enhance the current understanding of asteroidal environments and will yield key information for future human asteroid explorers.

A.4 To the Moon in a Shoebox: Engineering the Lunar Polar Hydrogen Mapper

S. West, C. Hardgrove, J. Bell (*Arizona State University*),
R. Starr (*Catholic University of America*), A. Colaprete (*NASA Ames*),
M. Robinsin (*Arizona State University*), D. Drake (*Techsource*),
I. Lazbin, G. West (*Arizona Space Technologies, LLC*),
E. B. Johnson, J. Christian (*Radiation Monitoring Devices*),
A. Genova (*NASA Ames*), D. Dunham, B. Williams, D. Nelson (*KinetX*), A. Babuscia
(*JPL/Caltech*), P. Scowen (*Arizona State University*),
K. M. Cheung, A. Klesh (*JPL/Caltech*), M. Tsay (*Busek Co. Inc.*),
S. Stem (*Blue Canyon Technologies*),
H. Kerner, R. J. Amzler, Z. Burnham, S. Puckett, N. Barba
(*Arizona State University*),
M. Beasley (*Planetary Resources*)

The Lunar Polar Hydrogen Mapper (LunaH-Map) will study the Moons south pole hydrogen deposits and place important constraints on their abundance and extent within permanently shadowed regions. The primary LunaH-Map science payload is the Miniature Neutron Spectrometer (Mini-NS) developed by Radiation Monitoring Devices (Wartertown, MA) and Arizona State University. After launch on Space Launch System (SLS) Exploration Mission 1, LunaH-Map will spend 70 days transferring to lunar orbit using its low-thrust, ion propulsion system. Once captured into lunar orbit, LunaH-Map will spiral down into a final science orbit with a periselene altitude of 10-15 km over the south pole. Science operations will last for approximately two months during which time Mini-NS will measure count rates of epithermal neutrons over the south pole. The LunaH-Map mission will conclude with a planned impact into a south pole crater.

As a 6U CubeSat, the LunaH-Map flight system is heavily resource constrained. In addition, the spacecraft must achieve and maintain a low-periselene orbit in the perturbed lunar gravity environment. Balancing these aspects of spacecraft engineering and mission design requires innovative solutions, particularly in areas of propulsion, attitude control, and operations.

The volume constraint of the 6U CubeSat form factor combined with the requirements of the mission design drove the selection of a low-thrust, gimbaled ion thruster as the sole propulsion system for the spacecraft. Without dedicated attitude control thrusters, the spacecraft relies on a set of reaction wheels for attitude control and the single ion thruster for momentum management. The offset between the thrust vector and the spacecraft center of mass allows the ion thruster to generate a moment and unload momentum from the reaction wheels.

The lunar transfer trajectory for LunaH-Map includes ~700 discrete low-thrust arcs. Limitations on the number and duration of tracking and communication passes require that the spacecraft have a high degree of autonomy. Multiple low-thrust arcs will be uplinked and stored onboard for sequential execution without ground intervention. The current science orbit design is “quasi-frozen” requiring no maintenance maneuvers throughout the nominal science phase. Studies are underway on the inclusion of a limited number of maintenance maneuvers to provide more consistent, lower periselene altitudes.

By leveraging the expertise and experience of the commercial small-satellite industry in combination with the resources available at ASU, LunaH-Map’s high-risk, high-reward mission stands to make meaningful contributions to lunar science.

A.5 BioSentinel – A Deep Space Radiation BioSensor Mission

Robert Hanel, James Chartres, Hugo Sanchez, and Vanessa Kuroda
(NASA Ames Research Center)

BioSentinel continues the design and development of a “6U” (10 × 22 × 34 cm; 14 kg) nanosatellite as a secondary payload to fly aboard NASA’s Space Launch System (SLS) Exploration Mission (EM) 1, scheduled for launch in late 2018. For the first time in over forty years, direct experimental data from biological studies outside the Earth’s Van Allen Belts will be obtained during BioSentinel’s 12-month mission. BioSentinel will measure the damage and repair of DNA in a biological organism and allow us to compare that to information from onboard physical radiation sensors. In order to understand the relative contributions of the space environments two dominant biological perturbations, reduced gravity and ionizing radiation, results from deep space will be directly compared to data obtained in LEO (on ISS) and on Earth. These data points will be available for validation of existing biological radiation damage and repair models, and for extrapolation to humans, to assist in mitigating risks during future long-term exploration missions beyond LEO.

Both the spacecraft bus and biosensor payload continue in their development as well more definition on the interface launch accommodations and safety processes to take advantage of the lunar flyby trajectory the SLS EM-1 affords. Several Engineering Development Units (EDUs) have been built and support Flight Software (FSW) in a flatsat development environment. These include a Linear Energy Transfer (LET) Spectrometer, BioSensor fluidic card assembly, Lightsey Space Research Cold Gas Propulsion System, Blue Canyon Technologies XACT 3-axis attitude sensor and control, MMA solar array and gimbal, and NASA Ames internal electrical power and switching boards.

As the BioSentinel spacecraft bus and payload developments continue to mature, the Concept of Operations (ConOps) and implementation of a supporting Mission Operations System (MOS) has continued. The ConOps has had to address the following areas, which are either new, or pose unique challenges to a nanosatellite mission:

- Allocation of functional responsibility between on-board functions and ground-based functions in support of operability of the spacecraft bus and payloads
- Determination of a communication pass plan and data budget that balances the need for downlinked data with strict S/C power and thermal constraints
- Planning for early mission activities that will occur during periods of high contention for communications assets

A.6 NASA's CubeQuest Awards Prizes to Citizens Demonstrating Advanced CubeSat Capabilities Useful for Deep Space Space Science Missions

Geza Gyuk, Mark Hammergren (*Adler Planetarium*),
and Alexander Ghosh (*University of Illinois*)

In June 2017, the NASA STMD Centennial Challenges Program's Cube Quest Challenge will announce the three teams of citizen inventors chosen to launch on EM-1 – the first lunar flyby mission of the Orion capsule aboard SLS. The selected CubeSats will be the top three winners – from a starting field of 13 competitors – of a series of Ground Tournaments culminating in GT-4, in May 2017. Teams may also find their own launch to compete in space.

Once teams manage to successfully demonstrate lunar orbit, or achieve a range of 4 mission km from Earth, they will compete to meet or exceed a number of communications data rate and data volume benchmarks to win cash prizes. There are also prizes for teams that successfully communicate with their satellite at the farthest distance from Earth, and that survive the longest in deep space or lunar orbit.

Cube Quest teams have proposed to demonstrate a variety of advanced technologies in deep space for the first time. Technologies include: Green Propellant, fuel from electrolysis of water, electric propulsion using iodized iodine; high-speed RF communications with a deployable antenna array and new ground segment facilities, and advanced GNC and ADCS technologies.

NASA's STMD expects the kinds of technologies demonstrated in Cube Quest will serve to advance CubeSat capabilities for discovery science missions envisioned by the National Academies of Sciences, Engineering and Medicine, Committee on Achieving Science Goals with CubeSats, report Achieving Science with CubeSats. The successful, Cube Quest technologies can contribute to advanced CubeSat capabilities with traceability to a variety of science mission scenarios, including missions in deep space that would support a number of NASA SMD future missions and decadal survey goals.

B.1 CubeSat Telecom System Needs for Deep-Space Missions

M. Michael Kobayashi and Tatyana Dobrevá
(*JPL/Caltech*)

With the growing number of deep space and interplanetary CubeSat missions, upgrades to various flight subsystems emerges as technological challenges for the flight system team. Popular radios used on Earth-orbiting CubeSat missions are capable of providing the command uplink and telemetry downlink from Low Earth Orbit, but lacks the necessary features to support deep-space missions. With an orbit trajectory outside the effective signal range of Global Positioning System (GPS) satellites, the navigation team will need to depend on radiometric tracking techniques to guide the CubeSat to the intended planetary body. To date, there is no CubeSat-class commercial radio available that can support these tracking techniques. The Iris Deep-Space Transponder was thus developed at the Jet Propulsion Laboratory to provide the basic communication needs alongside radio transponder features to support navigational products for precise orbit determination. This talk will focus on the CubeSat telecommunication subsystem needs for such missions, by first comparing the traditional CubeSat radios to the Iris transponder. Key specifications of the Iris transponder will be presented, and a brief design description of the hardware and signal processing features will be provided. A comparison against deep-space transponders used on traditional deep-space missions will also be presented to highlight the features and capabilities of the Iris transponder. Finally, future capabilities and ideas that will expand the use of the Iris transponder will be presented.

B.2 Inflatable Antenna for CubeSat at X-Band: Results of Experimental Tests

Alessandra Babuscia
(*JPL/Caltech*)

Interplanetary CubeSats and small satellites can provide means to explore space and to perform science in a more affordable way. However, the telecommunication systems currently implemented on CubeSats will need to improve to support interplanetary missions. One of the area of concern is the antenna. Hence, a possible solution is to develop inflatable antennas which can be packaged efficiently, occupying a small amount of space, and they can provide, once deployed, large dish dimension and correspondent gain. A prototype of a 1 m inflatable antenna for X-Band has been developed in a joint effort between JPL and ASU. The design is based on a spherical inflatable membrane that allows reaching a more stable inflatable surface, hence improving the electromagnetic performance. The antenna was fabricated, and tested at the anechoic chamber of Morehead State University in Kentucky. This presentation will detail the principle challenges in developing the new antenna and the results of the experimental tests.

Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

B.3 MarCO Telecom System Design

M. Michael Kobayashi
(*JPL/Caltech*)

The telecom subsystem of the Mars Cube One (MarCO) CubeSat mission utilizes several state-of-the-art technology, newly developed at the Jet Propulsion Laboratory, in order to support the real-time relay from the InSight lander during its entry, descent, and landing (EDL) sequence to Mars. An advanced deep-space transponder supporting radiometric tracking techniques for interplanetary navigation, and novel CubeSat-compatible deployable antennas are key devices that comprise this heavily telecom-oriented mission. Three flight units have been designed, assembled, and tested extensively, including performance tests against a channel simulator programmed to various predicted Doppler profiles to represent the dynamic environment expected during EDL. Compatibility tests to NASA's Deep Space Network (DSN) has been performed, and compatibility tests against InSight's UHF transmitter has been completed at the Lockheed Martin spacecraft integration facility. This talk will present the telecom system design, including a concept of operations detailing the spacecraft configuration, and results from various test campaigns will also be presented along with a discussion of some of the issues encountered during the development and lessons learned.

B.4 Development of Telecommunication Systems for EM-1 Interplanetary CubeSats Missions

K. Angkasa, A. Babuscia, N. Chahat, F. Davarian, C. Duncan, T. Dobрева, M. Kobayashi, J. Landa, C. Lau, D. Lewis, and A. Yarlagadda
(*JPL/Caltech*)

CubeSats are now providing a new way to explore space: they can be built by a smaller team, on a shorter schedule and on a smaller budget than traditional missions. For this reason, the development of CubeSats spread rapidly among universities, industries and government centers with currently hundreds of CubeSats launched in space. However, all the CubeSats launched so far are in Low Earth Orbit and they have very different needs from interplanetary CubeSats.

Interplanetary CubeSats and SmallSats face harsher environments, longer path distance and have more navigation needs than the LEO CubeSats. For this reason, the design of telecommunication systems for interplanetary missions is extremely challenging and a lot of development is currently ongoing in the areas of radio design, antenna design and ground support.

This presentation focuses on the telecommunication design for some of the interplanetary CubeSats missions that will be launched on SLS EM-1: BioSentinel, CuSPP, Lunar Flashlight, LunaH-Map, Lunar IceCube, NEAScout. Given the commonalities among these missions, an effort has been carried on at JPL to develop a common set of telecommunication hardware to fit the envelope of all the six missions goals and mission environments. This design approach is very unique for JPL, as compared to the traditional one of a kind design approach, that characterizes many JPL missions. However, this approach offers a considerable cost-saving-advantage, which is desperately needed for the interplanetary CubeSats missions to succeed. This presentation will provide a quick overview for each of the missions (including goals and telecommunication requirements) and it will also focus on the development of the telecommunication design with a particular focus on the Iris radio.

Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

B.5 Integrated Communications Antenna and Solar Arrays for Interplanetary CubeSats

Akshay Choudhari (*Arizona State University*),
Alessandra Babuscia (*JPL/Caltech*),
Jekan Thangavelautham (*Arizona State University*)

Interplanetary exploration requires a viable communication and tracking system that enables commanding, send telemetry and sending back meaningful science data to Earth. Small-satellites and CubeSats aim to cut down on the cost and complexity of interplanetary exploration. However, mass, volume and power are premium on these small platforms. We propose an innovative solution to reduce the after deployment volume of the CubeSat communication and power subsystem. Upcoming Interplanetary CubeSat missions such as MarCO include the use of X-band reflectarray antenna. Using a reflectarray antenna and a solar array independently for communications and power generation respectively could increase risk during complex maneuvers, such as aerobraking and science operations. Moreover, it also increases the after deployment volume and the risk due to multiple deployments (i.e. one for the antenna and one for the solar panels). A credible solution is to integrate both into a single component. A similar solution Integrated Solar Array and Reflectarray Antenna (ISARA), is currently in testing for Ka-band. We propose a similar hybrid of the NASA JPL X-band reflectarray antenna and MMA E-HaWK solar array. These two components can be modified and integrated together into a single component since they both share a similar form factor (6U x 3U after deployment). This can reduce the risks during aerobraking since the effective surface area after deployment would be lower than if they are used independently. Transmitting the data generally consumes more power and hence it is difficult to keep a CubeSat in transmit mode for a long time. Using the gimbal system, the reflectarray antenna located on one of the sides of the CubeSat can be Earth facing while the solar array can be Sun-facing. This will enable simultaneous operations of both, the solar panels and the reflectarray. This simultaneous operation can maintain longer communications link between Earth and the CubeSat. This is presuming continuous availability of the Deep Space Network (DSN) and limited blackouts during this period. We also study the use of Mars assets as an alternative to sending data back to earth, in addition to the direct X-band communication link to Earth. A UHF Transceiver designed to fit into a CubeSat could provide proximity communication with ExoMars, TGO and MRO. This can further increase the amount of data downlinked since the CubeSat data can be piggybacked to Earth via the higher data rate X-band communication link of the new and existing Mars orbiter assets.

C.1 Progress Toward Simultaneous Communications with Multiple SmallSats via a Single Antenna

Douglas S. Abraham
(JPL/Caltech)

As an increasing number of secondary payload opportunities open up for launch beyond GEO, more and more smallsats are looking to NASAs Deep Space Network (DSN) for communications support. To provide this support with the limited number of antennas at its disposal, the DSN has been pursuing a number of strategies for using a single antenna to simultaneously communicate with multiple, in-beam spacecraft. Opportunities for such beam sharing include the timeframe immediately following smallsat deployments from a launch vehicles secondary payload adapter, spacecraft “flotillas,” and virtually all spacecraft in orbit at Venus, Mars, or more distant locations. The DSNs strategies for facilitating such beam sharing include: (1) extending the DSNs existing Multiple Spacecraft Per Antenna (MSPA) capability from two in-beam spacecraft to four, (2) demonstrating and developing an Opportunistic MSPA (OMSPA) capability that can provide unscheduled, “open-loop” downlink to a virtually unlimited number of in-beam spacecraft, (3) exploring navigation techniques that would enable spacecraft to operate in a downlink-only mode for longer periods of time, and (4) investigating techniques for enabling Multiple Uplinks Per Antenna (MUPA).

With respect to progress on the first strategy, extension of existing MSPA capability, all DSN Complexes have recently been outfitted with the capability to support simultaneous downlink from four in-beam spacecraft. This 4-MSPA mode also enables the uplink to be serially swapped from one spacecraft to the next – allowing each spacecraft to operate in a 2-way, coherent mode for a portion of the total MSPA time.

In the case of OMSPA, 10 in-beam spacecraft simulations are being conducted using appropriately Doppler-shifted Iris radio recordings. These simulations are intended to demonstrate that all 10 downlink signals can be successfully retrieved, demodulated, and decoded from the same open-loop recording. Follow-on demonstrations involving multiple spacecraft at Mars are in the process of being initiated, and a prototype OMSPA user interface is currently under development.

Given that opportunities for 2-way coherent Doppler are limited when operating in 4-MSPA mode, and are nonexistent when downlinking via OMSPA, alternative navigation techniques are being studied. Results to date suggest that using 1-way Doppler supplemented by infrequent 2-way Doppler and/or delta-DOR measurements can provide reasonable navigation accuracies for low-cost smallsat missions.

Finally, different techniques for achieving MUPA are being investigated that may ultimately allow simultaneous uplink and 2-way Doppler during MSPA. Time-multiplexing uplinks from multiple spacecraft onto a single frequency looks particularly promising – though, spacecraft radio challenges remain pertaining to the support of non-standard turnaround ratios and the ability to scan for and lock onto a shared uplink frequency in cases where the differential Doppler shifts between spacecraft are large.

C.2 Enabling University-Operated Ground Support for Deep Space Small Spacecraft Missions—A Pilot Development with the Morehead State University 21 m Ground Station

Jeff Kruth, Ben Malphrus, Bob Kroll, Michael Combs,
Sarah Wilzkeski, Cody Robinson, Amber Myre
(*Morehead State University*)

Tim Pham, Jay Wyatt
(*JPL/Caltech*)

CubeSats are being planned for interplanetary research. EM-1 mission, with a plan to launch and deploy 13 accompanied Cubesats in 2018, will no doubt open the door for CubeSat and smallsat exploration of the solar systems. The new Cubesats will require communications, tracking, and navigation support that go could exceed the current capacity of the Deep Space Network, especially if all desired tracking needs from each Cubesat mission were to be met. Even with the expansion of the new antennas and with the implementation of new techniques to improve antenna utilization (i.e. multiple satellites per beam), the DSN is looking to find new low-cost approaches to support the unfolding smallsat revolution.

The goal of this project is to develop and implement a strategy that would integrate the Morehead State University 21 m antenna system into the DSN as an auxiliary station to support small-sat missions. This program will serve as a test case to define a path for integration of other non-NASA ground stations to support small-sat missions as well. The program focuses on the implementation of DSN capabilities, techniques and processes including deep space ranging, navigation and tracking techniques and capabilities, the implementation of Space-link Extension (SLE) protocol, CCSDS data standardization, and asset scheduling capabilities.

The ultimate deliverables of the two-year effort, to be completed in 2018, will be: 1.) DSN-compatible 21 m System Architecture Design that includes hardware and software upgrades necessary to provide deep space telemetry, tracking, and command functions, compliant with the CCSDS SLE specifications; 2.) Demonstration of the MSU 21 m antenna as a DSN-compatible operational node; 3.) Demonstration of ground system capabilities in demodulating and decoding cubesat telemetry data, accepting and transmitting commands to cubesat, and providing Doppler and ranging data for cubesat navigation; 4.) providing Doppler and ranging data for cubesat deep space navigation strategies and processes; and 5.) Compatibility with uplink and downlink processes implemented in NASAs Advanced Multi-Mission Operations System (AMMOS). The project will demonstrate a cost-effective solution for expanding DSN capabilities by utilizing non-NASA assets to provide significant support for CubeSat and microsat missions to the Moon, Earth-Sun Lagrange points, and Near Earth Asteroids; thereby enabling interplanetary research with small satellites. An overview of the project and the current status will be presented.

C.3 Enabling Deep Space Small Satellite Missions Using NASA AMMOS Products and Services

Eleanor V. Basillo and Peter Di Pasquale
affilJPL/Caltech

As the interest in using small satellites in deep space has grown, the related complexity of operations for small satellites has also increased thus driving the need for a highly-capable set of ground system tools.

Advanced Multi-Mission Operations System (AMMOS) is a set of multi-mission products and services that are common to deep space and planetary missions, and has a long history of supporting 50+ projects in development and flight operations. Recent developments have provided configurations that can be easily used by low-cost missions, such as cubesats. AMMOS for Cubesats enables ground system engineers to quickly deploy, configure, and operate a ground data system that is compatible with the NASA Deep Space Network. AMMOS provides missions with products and services in support of mission design and navigation, mission planning and sequencing, spacecraft health and performance analysis, mission control and flight system monitoring, information and data management, and instrument data processing.

For smaller missions, such as cubesats, we selected a limited set of AMMOS products and services configured to meet small satellite mission needs.

In the area of mission design and navigation, the AMMOS services available support orbit determination, trajectory propagation, maneuver analysis and design, and SPICE kernel production and data archiving.

In the area of mission planning and sequencing, the AMMOS products available include MPS Editor software, sample files, and corresponding documentation that would allow a small mission to create syntactically correct commands and sequences. Also, as part of mission planning, we provide scheduling services for the Deep Space Network (DSN) to ensure that your activities will have tracking coverage.

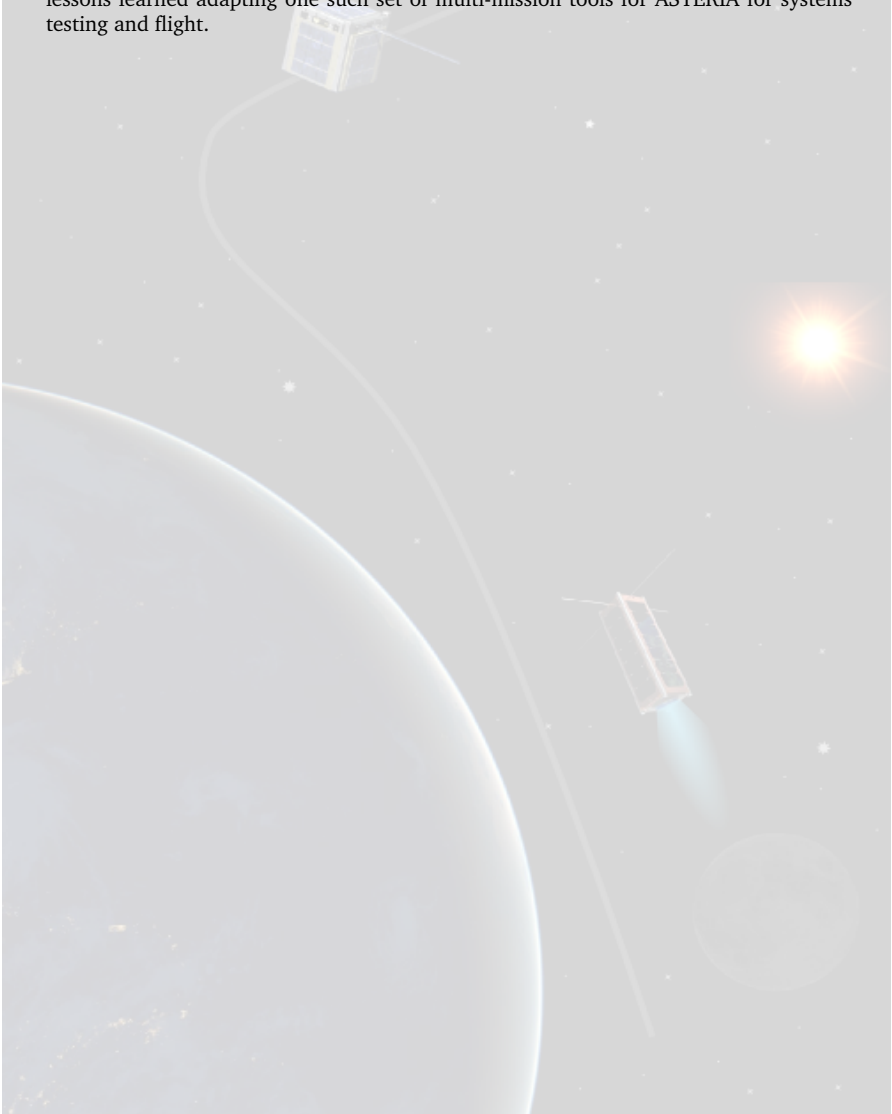
For mission control and flight systems monitoring functions, our AMMOS Mission Data Processing and Control System (AMPCS) is a flexible, real-time mission control application available for testbed and flight operations environment and is compatible with CCSDS formatted frames and/or packets.

For science data processing, we have tools available that excel in instrument telemetry processing (including early-phase development & test), instrument operations, science data system interfaces, mission operations process workflow, data distribution and science product archiving. Smaller, cost-constrained projects, such as cubesats, can easily carry those tools through operations.

C.4 End-To-End Systems with Multi-Mission Systems

Peter Di Pasquale (*JPL/Caltech*)

As small satellites grow in popularity, the engineers designing them have to face unique scenarios larger missions may have more flexibility solving; namely, that small satellite engineers must navigate a large number of commercial parts, existing networks, and existing software systems and integrate them all together. This presentation will cover lessons learned adapting one such set of multi-mission tools for ASTERIA for systems testing and flight.



D.1 Economical Mars Transits Outside the 26 Month Hohman Transfer Window

Darrin Taylor and Ricardo Staple (*Outer Space Colonization*)

Typical transits to Mars are constrained to a small window every 26 months. Transits outside this window are rendered impractical by the rocket equation that governs all thrust methods which carry their own reaction mass.

The Transferred Momentum method uses solar sail powered “brick” spacecraft as non carried, reusable reaction mass for a “pusher” class spacecraft. This allows the “pusher” spacecraft to outperform rocket fuel in terms of consumed mass fraction while also vastly outperforming Ion Propulsion acceleration levels.

The physics behind this is simple. Because photons are inexhaustible during the life of the sun the solar sail powered “brick” spacecraft can maneuver to any point in the solar system at any desired velocity, provided the spacecraft useful lifetime has not been exceeded. Reaction mass “bricks” can be deposited with position and velocity matched to the “pusher” so that a very low relative velocity docking maneuver is all that is needed to dock with and refuel the “pusher”.

During lifetime of the “bricks” and “pusher” the reaction mass can be reused and repositioned. The “pusher” is making many small delta V maneuvers and refueling in-between, while rocket fuel must perform a large delta V maneuver because it can’t refuel effectively in transit. This allows the 25.5 s Isp of the pusher to outperform on average the 453s Isp of rocket fuel given a sufficiently long useful lifetime of the “bricks” and “pusher” components. In addition, at end of life the “bricks” and “pusher” can be remanufactured in space and the mass can be recycled extending the useable lifetime far far beyond the target 30 years.

The end result is Transferred Momentum is able to leave outside the 26 month Hohman transfer window execute a much larger delta V transit and still compete on consumed mass fraction with rocket fuel transfers that leave inside the Hohman window and execute the minimum delta V transit. Performance competitive with $>5000s$ Isp and $>10 \text{ mm/s}^2$ appears possible.

D.2 Interorbital Systems: Launch Services to LEO, LUNA, and Beyond

Randa Relich Milliron
(*Interorbital Systems*)

The expense of buying passage for a small satellite payload is often more than a small business or an academic institution can afford, and usually more than a government or military entity would like to spend. Waiting for an opportunity to launch as a secondary payload is often a frustrating, if not endless process. Global competitions among hundreds of student satellite projects for these rare flights leave all but the one or two lucky winners without a ride to orbit. An inexpensive, dedicated launcher; an assortment of affordable small satellite kits; and low-cost, rapid-response launch services are urgently needed to create and carry small experimental, academic, government, art, and military payloads to orbit. Interorbital Systems NEPTUNE modular rocket series: N3; N5; and N8 LUNA; and IOS' Personal Satellite Kits will fill those needs. For example, the N5 is designed to launch 24 picosats at a time, for as little as \$8,000 each, or from \$1.5 million for a single dedicated 30-kg payload capacity. The popularity of this new service is evidenced by Interorbital's current orbital launch manifest of 137 picosats for upcoming sold-out LEO Missions I-V. Flight-testing continues with orbital launches beginning summer of 2017, plus two Q4 Moon missions: Lunar Bullet and Google Lunar X PRIZE.

Partial Payload Manifest: UC Irvine; Google Lunar X PRIZE Teams EuroLuna, Plan B, Part-Time Scientists, and SYNERGY MOON; FPT University, Vietnam; Nanyang Technological University, Singapore; King Abdullah University (KAUST), Saudi Arabia/US; NASA IV& V Facility; Institute of Space Technology, Pakistan; Taiwan National Cheng Kung University; Morehead State University (Kentucky Space); InterAmerican University of Puerto Rico; University of Sydney; Aslan Academy; Project Calliope (Space Music); Universidad de Puerto Rico/Marcelino Canino Middle School; Naval Postgraduate School; Defense Science Technology Lab (DSTL, UK); Austrian arts group mur.at; USMA at West Point; Brazilian Space Institute/Ubatuba Middle School; ULISES Sat, Space opera, Mexico; TriVector Services; AKQA, SF; La Despensa, Spain; The Golden iPod, Bishop, CA; IAMAS, Japan; Galaxy Global; and Universidad de Chile. University Sao Paulo, Integrated Systems Lab, Brazil (2); David Lawrence K-8 School, North Miami; Optimize-EduSat; RADG; OMNI LABS (Brazil); 4-H/Ute Mountain Ute/Colorado State University Extension; KEN KATO, Japan; Ryerson University, Toronto; TARDIS in Orbit; Spacebooth, Belgium; Boreal Space (US)/M2M2Space, Brazil; Space Lion Rufs, Sweden; and Uninova Instituto, Portugal, National University of Singapore, IBM, Ars Technica; Mountain View High; Ariel University R&D, Israel; NoiseFigure Research; Shasta College; Solarem UK; Base 11/West LA College; and the MITRE Corporation.

D.3 Solar Thermal Propulsion for Interplanetary Small Satellites

Salil Rabade, Jekan Thangavelautham, Mercedes Herreras-Martinez,
Andrew Warren, Aman Chandra, and Ravit Teja Nallapu,
and Erik Asphaug
(*Arizona State University*)

The miniaturization of electronics, sensors, actuators and power systems are enabling small spacecraft for interplanetary exploration. These spacecraft are typically designed to ride along with a larger spacecraft or be deployed in a mother-daughter configuration due to limitations with propulsion. These dependencies can impact the small-spacecraft mission from launch delays and integration challenges of the larger mothership. A small-spacecraft with its own independent and capable propulsion system can avoid these challenges. State-of-the-art chemical propulsion systems for small satellites, such as green monopropellant perform combustion, but produce high-thrust and high delta-v. Electric propulsion systems such as hall-thrusters produce high Isp but require high-power, typically relying on large solar panels and produce very low thrust. Both high-thrust and high Isp systems on a single spacecraft propulsion system offers substantial new benefits. We present use of water-steam as a propellant. Use of water steam is not an entirely new idea. Previous work has proposed use of nuclear reactors to heat water into steam to produce thrust. Our approach utilizes solar-thermal concentrators assisted with carbon nanoparticles such Vantablack® to heat water to temperatures of 1000 to 3000 K. The technology is applicable for interplanetary travel in the inner solar system. Our theoretical results show Isp of 190 s to 320 s are achievable. Furthermore, this water-stream propulsion system can be throttled between high-thrust and high-Isp configurations. We present preliminary laboratory experiments to demonstrate key component technologies. Water steam propulsion is simpler than electrolyzing water to produce hydrogen and oxygen for combustion but at the price of reduced performance. In addition, water steam propulsion can be an enabler for In-situ Resource Utilization (ISRU) of Near Earth Asteroids (NEAs) and comets, as some of these small bodies are known to harbor substantial quantities of water. The water does not need to be purified or distilled of impurities. However, when further performance is required beyond what is possible with steam-propulsion, water electrolysis maybe used to generate high thrust and higher Isp. Our approach outlines a pathway towards making water a simple and viable propellant for interplanetary travel.

E.1 SunRISE: Sun Radio Interferometer Space Experiment

Farah Alibay (*JPL/Caltech*), Justin Kasper (*University of Michigan*), Joseph Lazio (*JPL/Caltech*), and Tim Melsen (*Utah State University*)

We present a space-based array, composed of six 6U CubeSats, designed to localize the radio emission associated with coronal mass ejections (CMEs) from the Sun. Radio emission from CMEs is a direct tracer of the particle acceleration in the inner heliosphere and potential magnetic connections from the lower solar corona to the larger heliosphere. Furthermore, CME radio emission is quite strong such that only a relatively small number of antennas is required, and a small mission would make a fundamental advancement. This type of Heliophysics mission would be inherently cost prohibitive in a traditional spacecraft paradigm. However, the use of CubeSats, accompanied by the miniaturization of subsystem components, enables the development of this concept at lower cost than ever before.

We present the most recent updates on this mission concept, starting from the science and driving technical requirements. The presentation then focuses SunRISE architecture, which is composed of six 6U CubeSats placed in a GEO graveyard orbit for 6 months to achieve the aforementioned science goals. The spacecraft fly in a passive formation, which allows them to form an interferometer while minimizing the impact on operations complexity. We provide an overview of the most challenging mission and spacecraft design aspects, as well as an overview of the concept of operations.

E.2 Morph

Steve Matousek
(JPL/Caltech)

The convergence of greatly increased small satellite capability and cooperative drones enables a new architecture for space exploration. Morphing multi-unit multi-functional spacecraft can adapt to science and mission goals and objectives. The morph spacecraft can change shape and configuration with mission phase. This new architecture enables new types of science and missions not achievable with stand-alone or mother-daughter architectures. The morph architecture takes advantage of physical contact between units and the ability to change the shape of the aggregate spacecraft throughout the mission. One or more units can also be deployed during the mission as probes. Examples of this emergent capability include the Caltech Autonomous Assembly of a Reconfigurable Space Telescope (ARReST) telescope aperture CubeSat with magnetic assisted physical connection (<http://www.pellegrino.caltech.edu/aarest1/>). And, numerous examples of Earth-based drones cooperating to accomplish a task not possible with a single drone. One notable example of this is research on-going at Caltech to wash skyscraper windows. The system challenge is in the software that enables cooperation and reconfiguring the multi-unit (drone) architecture. Lastly, some representative configurations versus mission phase and standard single spacecraft are compared including rough cost.

E.3 Small Asteroid Impactor in Near Trans-lunar Space (SAINTS)

Geza Gyuk, Mark Hammergren (*Adler Planetarium*),
Alexander Ghosh (*University of Illinois*)

SAINTS would be a small-satellite ($\sim 24U$) mission to examine the response of a 50-m class Near Earth Asteroid to an impact with energy far in excess of its gravitational binding energy and to provide detailed examination of its morphology and surface features. SAINTS will further our knowledge of key science and engineering objectives defined by NASA: to study the interior composition of small asteroids, to study the ability to deflect/destroy them using kinetic impactors, and to test the ability of CubeSats to operate outside of Low Earth orbit (LEO).

SAINTS would take advantage of the abundance ($>500,000$) of 50-m class NEAs to conduct the impact in near trans-lunar space (<3 LD). Targeting this region of space will allow use of Earth-based and space-based (such as Hubble) resources to supplement the in situ observations of the asteroid, impact and aftermath. Critically this would allow radar, photometric, astrometric and spectroscopic follow-up allowing characterization of the debris cloud, possible orbit modification, and surface overturn in the hours, days and weeks following the impact. Additionally, operations in near trans-lunar space would take advantage of reduced delta-V needs and lower power requirements for the communication system, while still posing a significant deep space satellite design challenge on which to prove small satellite technology for future missions.

SAINTS would consist of a mothership and a deployable impactor. The mothership would provide images of the asteroid from multiple perspectives, high-speed imaging of the impact itself, and post impact monitoring of the debris cloud. It would additionally serve as the data relay for images and data collected by the impactor. The impactor would also contain a high-speed imager allowing examination of the surface until the moment of impact.

The SAINTS spacecraft would be launched into a geosynchronous transfer orbit or other similar very elliptical orbit. Over the course of the next year SAINTS would gradually raise its apogee and modify its orbital orientation using a solar electric propulsion system and lunar gravity assists. If necessary limited impulsive boosts would also be utilized. During this process the orbital phase will also be adjusted to ensure intersection of the spacecraft and asteroid orbits in both location and time. Avoiding the need to match velocities allows a much greater space of orbital solutions, considerably reducing the technical difficulty.

E.4 Spacecraft Penetrator for Increasing Knowledge of NEOs (SPIKE)

Erik Asphaug, Jekan Thangavelautham, Stephen Schwartz
(*Arizona State University*)

Daniel Scheeres (*CU Boulder*), Roberto Furfaro (*University of Arizona*), and
Mathieu Choukroun (*JPL/Caltech*)

Hundred-meter asteroids represent a unique niche in interplanetary exploration: they are common and important (to science, hazards and resources) and a spacecraft can land on them in free-fall (escape velocity ~ 10 cm/s). The advent of ESPA-class Solar Electric Propulsion technology allows us to design a low cost, robust strategy for multi-NEO landers that deploy penetrators at the end of a meters-long boom, to conduct subsurface volatile and organics determination and seismology. The SEP bus is kept at safe distance from the surface, landing in an inverted pendulum configuration atop the science payload. In the very low gravity environment (< 0.1 cm/s²) the spacecraft arrives and departs using SEP; a slight mechanical push allows liftoff for a series of landings, and a journey to a second and possibly third NEO, without requiring a chemical propulsion system.

E.5 SunCube FemtoSats: A New Tool in the Interplanetary Exploration Toolbox

Jekan Thangavelautham, Mercedes Herreras-Martinez, Andrew Warren, Aman Chandra, Ravi Teja Nallapu, and Erik Asphaug
(*Arizona State University*)

The rapid miniaturization of electronics, sensors and actuators has led to the growth of low-cost small-satellites and CubeSats. Importantly, CubeSats and small-satellites are emerging as credible options to perform short, focused science missions that would otherwise not be possible with Discovery, New Frontier and flagship class missions. Their small size can provide an advantage over conventional large satellites, through the use of constellations and swarms that can observe many targets at once, produce high resolution observations or sample dynamically varying fields. However, CubeSats and small-satellites are still relatively large and costly, putting out of reach most businesses, research institutions and individuals. They are often too costly for development of constellations and swarms of spacecraft. We propose the SunCube FemtoSat 1F, a spacecraft that is 3 cm × 3 cm × 3 cm and 35 grams in mass. Each SunCube FemtoSat is equipped with a 32-bit ARM microprocessor, UHF communication system with an expected range of 500 km, 3 MP camera and triple junction solar panels. A baseline design would use magnetorquers for attitude control. These miniature spacecraft can match the capabilities of first generation 1U CubeSats launched during the 2003-2005 timeframe. A variant of the FemtoSat 1F is the 3F, which is a 9 cm × 3 cm × 3 cm and has a mass of 100 grams, with 2/3 of the volume and mass reserved for a payload. The parts costs are expected to be \$300-500 a spacecraft and launch cost to the ISS starting at \$1,000, with LEO free-flight starting at \$3,000. The starting price for interplanetary launch is expected to be \$27k for the 1F and \$81k for 3F. The SunCube FemtoSats are designed to be launched using the standard CubeSat PPOD using an adapter. It is envisioned that a typical 3U PPOD could host 81 1Fs or 27 3Fs. The ability to host scores of SunCubes aboard a large spacecraft for low-cost can provide entirely new operational capabilities for mission planners. This includes dropping-off SunCubes at strategic times to monitor many phenomena at once, performing spacecraft selfies and for performing high-risk, high-reward science.

E.6 Detailing small-body surface properties with the Asteroid Mobile Imager and Geologic Observer (AMIGO)

Stephen R. Schwartz, Erik Asphaug, Jekan Thangavelautham,
Laksh Raura, Salil Rabade (*Arizona State University*),

Christine M. Hartzell (*University of Maryland, College Park*)

Understanding the granular material dynamics of small Solar System bodies (SSSBs) in their native small-body gravitational environment is vital for the correct interpretation of their surface geology. It is also critical for the design and/or operation of any device intended to interact with their regolith-covered surfaces, which must accommodate powdery low-cohesion, low-friction textures, as well as the hardest rock types in the meteorite collection. A comprehensive understanding of an SSSB requires a global exploration of its likely diverse locales (e.g., surface gravity, rock size, sun exposure, and thermal inertia, all vary from point to point on the their surfaces). The Asteroid Mobile Imager and Geologic Observer (AMIGO) would be deployed at multiple locations around the surfaces of small bodies and provide stereo imaging from vantage points ~ 1 m above the surface, close-up geologic imaging, electric field measurements, thermal fatigue assessments, and seismic sensing. The payload consists of three or more 1U CubeSats that each contains an inflatable package. Once deployed from a mother spacecraft positioned above a small body, each CubeSat will inflate to attain a 1-m ovular shape. Ejected during a slow flyby, the AMIGOs descend to the surface, acquiring their first science and context images. They impact at approximately 15 cm/s, experiencing a series of low-speed bounces to come to rest, upright, at a random location on the surface. The low-pressure membrane easily survives such bounces and the strongly bottom-weighted design will help to ensure that it comes to rest in a close-to-vertical position. The lightweight inflatable self-righting design offers key advantages compared to other nano-landers: it gives them reflective properties and cross sections that allow them to be identified and tracked, so they are not lost beneath the surface regolith and dust to the mothership overhead (a noninflating 1U cube could easily become lost or buried in typical asteroid terrains and is smaller than the global imaging resolution of the spacecraft). By raising the binocular pair of cameras to 1-m height, without use of mechanisms, these panoramas see beyond nearby rocks and small boulders to provide surface context. The inflatable design also ensures that each AMIGO has its solar arrays in sunlight, without any requirement of mechanisms or avionics. The inflated shell is also beneficial to concentrating available solar power and operates to support an array of electric field sensors, and as a passive sensor (via photovoltaics) of dust loading.

E.7 ATROMOS: USING NANO-SATELLITE TECHNOLOGY TO EXPLORE THE MARS SURFACE

Marcus Murbach (*NASA Ames*), P. Papadopoulos (*SJSU*),
D. Atkinson (*University of Idaho*), AliGuarneros Luna (*NASA Ames*)

A low-cost mission is proposed which would place two 10kg-class science stations on the surface of Mars. The mission proposal consists of an ‘enabling’ probe entry system – and is comprised of a unique Entry/Descent/Landing (EDL) system based on the Tube Deployed Re-entry Vehicle (TDRV). Requiring minimum interface constraints to the carrier spacecraft, the TDRV is a self-orienting, low ballistic coefficient entry system which has been tested during sub-orbital test flights. As a two point network, one of the science scenarios consists of landing a probe inside the Southern hemisphere Hellas Basin and the other on the exterior at significantly higher elevation. This two point system can provide information related to climatic and geological/hydrological gradients. The investigation would help validate models which seek to explain the South Polar asymmetry (Colaprete, et al. 2005), as well as fundamental saltation phenomena, critical to understanding dust lifting and the genesis of large-scale dust storms. The surface science station can also provide a platform for performing basic mineralogy and perhaps life detection. In addition, recent advances in the development of small radioisotope power sources can contribute to subsequent missions of multi-year duration. While proposed as an inexpensive means (taking advantage of rapid advances in CubeSat based technologies) of injecting new sensor technologies at higher risk sites, this architecture set can also grow into a future large scale climatology/geophysics network mission.

F.1 Use of Shape Memory Alloy Actuators for Precise Pointing on Interplanetary Small Satellites and CubeSats

Nikhil Sonawane and Jekan Thangavelautham
(*Arizona State University*)

Interplanetary small space systems require precise pointing to observe fixed targets over prolonged time both for communications and science/exploration. Mass, volume and power are a premium on these small platforms. Conventional actuator technologies face major challenges in scaling-down to these small configurations. Conventional systems typically use reaction-wheels or thrusters to slew the spacecraft and gimbaling systems containing motors to achieve precise pointing. Motor based actuators have limited life as they contain moving parts that require lubrication in space. Alternate methods have utilized piezoelectric actuators. This work presents Shape memory alloys (SMA) actuators as an alternative for control of a deployable antenna placed on a small satellite. SMAs are typically metal alloys that transition from one phase to another due to relatively small changes in temperature. The alloy changes phase and thus can take on one or more structures, which enables them to have large packaging efficiency in constrained volumes like small satellites and CubeSats. The SMAs are operated as a series of distributed linear actuators. These distributed linear actuators are not prone to single point failures and although each individual actuator is imprecise due to hysteresis and temperature variations, they can collectively produce robust results. Efforts are focused on developing a system that can achieve one degree pointing accuracy at first, with an ultimate goal of achieving a few arc seconds accuracy. Bench top demonstrations of the actuator system have been developed and we are working towards testing the system under vacuum. A demonstration flight of the technology is planned aboard a CubeSat.

F.2 Autonomous Surface Mobility on Small Solar System Bodies with Hopping/Tumbling Rovers

Benjamin Hockman, Marco Pavone
(*Stanford University*),

Andreas Frick, Julie Castillo-Rogez, Robert Reid, Issa Nesnas
(*JPL/Caltech*)

The future in-situ exploration of small Solar System bodies requires robotic platforms capable of controlled surface mobility. In the microgravity environment of small bodies such as asteroids, comets or small icy moons, conventional wheeled rovers are quite ineffective due to the low frictional forces on the ground. Through a joint collaboration between Stanford University, JPL, and MIT, we have been developing a small, minimalistic rover, called “Hedgehog”, which extends the idea of internal actuation, previously developed for landers on the Hayabusa II mission, to an architecture that enables controlled surface mobility in microgravity. Specifically, by applying torques to three internal flywheels with motors and mechanical brakes, Hedgehog is capable of performing attitude-controlled hops for large surface coverage, “tumbling” maneuvers for fine local mobility, and precise shifts in orientation to point instruments. Such a mobility approach is critically enabled by the microgravity environment of small bodies, whereby small surface contact forces can produce long-range ballistic flight.

We have demonstrated controlled mobility in simulation, in a high fidelity microgravity test bed, and onboard NASA parabolic flights. However, navigating a hopping rover to points of interest on the surface of distant bodies requires more than just controlled maneuvers. It also requires an autonomy stack that allows the rover operate independently without continuous communication with ground stations specifically, the ability to localize itself on the surface and plan safe trajectories in a potentially hazardous environment. We adapt concepts from the fields of vision-based localization and reinforcement learning in robotics for the unique visual environment on the surface of small bodies and for the highly stochastic dynamics of hopping and bouncing.

This concept has the potential to lead to small, quasi-expendable, and maneuverable rovers that enable a focused, yet compelling set of science objectives aligned with interests in planetary science and human exploration. Moreover, this new paradigm of mobility for “nanorovers” is highly scalable within typical CubeSat sizes from 1U to 27U, allowing many of the subsystems to be leveraged from interplanetary CubeSats being developed at JPL (e.g., C&DH/avionics boards from NEA Scout, UHF telecom system from INSPIRE, and electrical power system from MarCO). We present a notional mission architecture to Phobos that addresses both high-priority science identified for Mars’ moons and strategic knowledge gaps for the future Human exploration in the Martian system.

F.3 Inflatable Entry, Descent and Landing System for CubeSats

Erik Asphaug, Mercedes Herreras-Martinez and Jekan Thangavelautham
(Arizona State University)

Flagship missions to the surface of Mars carry ballast in the order of 100 kg. This ballast mass could be utilized to carry CubeSat landers. A CubeSat lander can complement a large flagship mission by providing in-situ science in multiple locations on the surface of Mars at once. We propose to develop an inflatable atmospheric entry system for CubeSats that has two major goals. One is to develop an entry system for deployment of CubeSats onto planets or moons with an atmosphere. The second is to provide insight into the development of a High Mass Mars System (HMMS) by using the Inflatable Aerodynamic Decelerators (IAD) concept. Our goal is to safely land an entire 6U, 36cm×24cm×12cm CubeSat. Our proposed technology consists of an inflatable entry system that has a low-ballistic coefficient and is of low-cost and low-complexity. The inflatable entry system contains multiple redundant bladders (cells) made of Vectran®, where even if one or a few are damaged, the system can maintain its shape. The bags are inflated using a solid-state chemical generator to produce nitrogen. The layers are hardened using a heat-curing resin. The entry system will be slowed down using a subsonic parachute and crumple upon impact and absorb the brunt of the impact energy. In this presentation, we perform a preliminary trade study and analyze both the challenges and opportunities with the proposed inflatable EDL system.

F.4 Radiometric Actuators for CubeSat Attitude Control in Deep Space: A Comparison between Analytical and Computational Models

Ravi Teja Nallapu and Jekan Thangavelautham
(*Arizona State University*)

CubeSat capabilities are rapidly growing, enabling a diverse number of applications including earth and astronomical observations, demonstration of new space technologies and for use as on-orbit science laboratories. However, their full benefits are presently limited to Low Earth Orbits (LEOs). Among the several challenges for Higher Earth Orbits (HEOs) and other deep space trajectories, a very important challenge is that of the attitude control. Typically, CubeSats use magnetorquers and reaction wheels to perform attitude control. Once the reaction wheels are saturated, magnetorquers are used to desaturate them. In deep space, attitude control thrusters that expend propellant are used to desaturate the reaction wheels. Once the spacecraft runs out of propellant, it loses its ability to desaturate its reaction wheels. We develop alternate technologies that perform attitude control without having to expend propellant. This presentation discusses how radiometric forces: forces appearing on thin vanes containing rarefied gasses in the presence of a temperature differential can be applied to solve the deep space attitude control problem and without using propellant. The design of the actuator is briefly presented here, along with a discussion of a conceptual CubeSat based telescope mission in deep space. A major emphasis in this presentation will be comparison between different radiometric force models. The analytical model of the radiometric force derived from statistical mechanics is compared to computer based molecular simulations which use the Direct Simulation Monte Carlo (DSMC) technique. The molecular dynamics software SPARTA, which is open source software from Sandia National Labs is used for the molecular model. Finally, the results are then compared, and the conclusions of such an actuator are presented.

F.5 Liquid reaction wheel, based on MHD effect in liquid Mercury

Giorgi Veshapidze, David Chkhaidze,
David Kvavadze, Giorgi Tsomaia
(*Ilia State University, Tbilisi, Georgia*)

We report on the development of reaction wheel for spacecraft attitude control. Unlike conventional reaction wheels, where the control is achieved through the rotation of rigid wheels, the developed solution employs liquid Mercury, moving in the circular canal. The side walls of canal are made from steel, which does not react with Mercury chemically. Top and bottom are made from Teflon, which are also chemically inert regarding Mercury. At the top and bottom of the canal are placed two ring-shaped permanent magnets, which create ~ 1 T magnetic field in whole volume of mercury. The motion of Mercury in canal is induced by applying current between steel sidewalls of canal, through mercury. In magnetic field the Ampere force will act on currents, in whole volume of liquid Mercury, directed perpendicular to both, magnetic field, and current, that is along the canal.

Besides staying liquid down to -38.8290 °C, Mercury offers an advantage of high density, higher than even Lead. Another envisioned advantage is simplicity of construction and operation, which one could translate into higher reliability.

F.6 How small is a small spacecraft? Size versus autonomy in planetary spacecraft?

Frank Crary, David Brain, Nick Schneider,
Laila Andersson, Scott Palo
(*University of Colorado, Boulder*)

Concepts for small planetary spacecraft range from 1U CubeSats to 180 kg ESPA-class spacecraft. The former may only be practical as a secondary payload associated with a larger mission, while the later could be an autonomous and stand-alone mission. In addition to instrument complement, key issues include telecommunications (direct to Earth or relayed by a parent spacecraft or carrier vehicle), propulsion and navigation (carried to the desired orbit by another spacecraft versus operating independently.) The optimal size is a balance between the capabilities of the small spacecraft and its impact on a larger mission, or the need for a supporting carrier vehicle. We will discuss these tradeoffs and illustrate them using a number of planetary small satellite concepts.

G.1 Expandable Hybrid Computing Platform for SmallSats

Katherine Conway, Vert Vermeire (*Space Micro Inc*),
Chris Wilson, and Alan George (*University of Pittsburgh*)

Interplanetary missions have a variety of needs for autonomous processing and control. Proposed future mission concepts expect to have more computational resources at their disposal, while operating in smaller spacecraft with stringent SWAP and cost requirements. The CHREC Space Processor v1 (CSPv1) follows a hybrid design philosophy, which surrounds appropriate commercial parts with space-qualified parts to achieve the performance and energy efficiency of a commercial processor with space-qualified reliability. CSPv1 combines a Xilinx Zynq-7020 (with dual ARM cores and re-configurable FPGA fabric), DRAM (with SECEDED coding), radiation-tolerant flash memory (stores multiple boot image copies and user data) with radiation-hardened components for critical systems supplemented with software mitigation for soft errors, all within a 1U printed circuit board. Details of its design and feature set can be found in prior work. CSPv1 forms the computing core of a number of space experiments demonstrating its versatility as a high performance, conveniently expandable computing platform. This paper discusses the expandability, reliability, and future missions for CSPv1.

Customization and hardware expansion are available for CSPv1 through its dense, high-speed 160-pin backplane connector. CSPv1 supports SPI, JTAG, UART, I2C, CAN and Ethernet. The FPGA fabric and backplane connectivity make it possible to add interfaces such as RS-422, RS-485, high speed point to point links or SpaceWire. CSPv1 can be configured with several commercial and open-source operating systems for usability and real-time capability including Linux, RTEMS, and VxWorks. Board-support packages with drivers and applications are available for both RTEMS and Linux platforms. Ancillary testbed development boards provide key interfaces such as Ethernet, JTAG, UART, SpaceWire, CAN, Camera Link, USB, and spare single-ended and differential signals. Flight versions of CSPv1 support NASA Goddards reusable flight software framework Core Flight Executive (cFE) along with several key Core Flight System applications.

CSPv1 is available in parts grades from commercial space to EEE-INST-002 Level 2. It is manufactured to NASA 8739 workmanship standards, is available with TID tolerance of 30krad or 100krad and immune to destructive single events. Both the ARM cores and the FPGA fabric are susceptible to SEU which are mitigated with various scrubber configurations (blind, readback, or frame-ECC) and watchdog. Block-level TMR can be used in combination for greater reliability. Missions should still tolerate the occasional unexpected reset when the watchdog trips.

Several missions currently in design are using CSPv1's expansion options. A software-defined radio (SDR) consisting of CSPv1, a 1U modem configured for 70MHz IF with 10MHz bandwidth and S-band RF module will be used to evaluate hardware, waveforms and networking protocols for a cluster of CubeSats. A wideband software-defined transmitter (400–4100MHz) with STRS operating environment to provide hardware abstraction for third party waveform development is also being designed. Several CSPv1 boards are to be featured on an upcoming experiment to demonstrate high-performance computing on a clustered and networked space platform. This mission features configurable point-to-point links with networking protocol as the inter-processor communication. The cFE software bus, modified to include OMG Data Distribution Services to support inter-node, publish-subscribe functionality supports communication between all processors.

G.2 Analysis & Design Of Small 6U CubeSat For Future Space Exploration Missions

Md Mahbubur Rahman and Mazher Ali

(Skolkovo Institute of Science and Technology, Skolkovo, Russia)

Over the coming decade, Interplanetary CubeSat's are enabling small, low-cost missions beyond the LEO (low earth orbit). This class is defined by mass $< \sim 10$ kg, cost $< \$30$ M, and lifetime up to 5 years. In the lifetime, depending on the mission to Mars, Moon or different planet this CubeSats are subjected to the hazardous environment. In order to maintain structural integrity throughout the mission, the design of structural subsystem has to survive launch loads and a suitable environment for the operation of all subsystems throughout all the phase of the mission life, providing and easily accessible data and power bus for debugging and assembly of components

In this paper, we analyze the optimal structural and thermal design for 6U CubeSat for future solar system exploration projects. The structural subsystem design, preliminary stress analysis will be performed to optimize the design with specific mission constraints. CubeSat thermal analysis conducted considering uneven temperature distribution for different orbits. Thermal analysis includes radiation from sun and earth also internal heat generation and conduction encountered during the mission operation. In the end of this paper, an optimal design was proposed for the CubeSat.

G.3 Effective CubeSat Fault Management Strategies Beyond Low Earth Orbit

Matt Sorgenfrei, Doug Forman, Mike Logan, Hugo Sanchez
(*NASA Ames Research Center*)

Fault management operations are challenging for spacecraft of all sizes, but are particularly challenging for CubeSat-class spacecraft, which are subject to much stricter mass, volume, and power constraints. The difficulties of effective fault management are further exacerbated for CubeSats operating beyond low Earth orbit (LEO). In these distant orbits it is not possible to use the Earth's magnetic field for attitude determination and control, and communications must be routed through NASA's Deep Space Network (DSN). One example of this challenging fault management environment is the upcoming BioSentinel mission, a six-unit (6U) CubeSat that will operate in an Earth-leading, heliocentric orbit beyond the Van Allen Belts. BioSentinel is equipped with a three-axis attitude determination and control system built around three reaction wheels and a star tracker, a cold gas propulsion system, and an advanced radio capable of communicating with the DSN. The science objective of the mission is to study the impact of deep space radiation on Eukaryotic cells, providing scientists greater insight into what the impact would be on astronauts during future manned missions beyond LEO.

This presentation will describe the fault management system currently under development for BioSentinel. The on-board fault management software is responsible for continuously querying a range of outputs, known as Watch Points, from all of the spacecraft subsystems and acting upon those outputs—often in a semi-autonomous or fully autonomous manner. The current operations plan for BioSentinel will only allow for relatively limited communications with the DSN, so in some cases the fault management software will be expected to autonomously respond to certain Watch Points being out of range. This ensures the spacecraft will not damage itself prior to intervention from operators on the ground. This presentation will detail the Watch Points that have been selected for a number of the spacecraft subsystems, and will discuss what actions (if any) can be taken when these Watch Points move out of their acceptable ranges. Additionally, the interaction between the planned fault management system and the broader flight software architecture will be outlined, with particular attention paid to on-orbit operations. BioSentinel uses the Integrated Test and Operations System (ITOS) open-source software for testing and mission operations, and results from a variety of tests being conducted on the spacecraft engineering development unit using ITOS will be presented herein.

G.4 Saberwing: An Interplanetary SmallSat Technology Demonstration

Jeremiah Pate (*LunaSonde*),
Collier Moody (*Embry-Riddle Aeronautical University*)

Saberwing is a 6U CubeSat mission with the objective of exploring the moon while testing several new technologies. It is also a potential contender for the NASA CubeQuest Challenge. Although low earth orbit has been revolutionized by nanosatellite design, deep space/ lunar exploration have varied little from multimillion dollar missions. In order to expand the scope of planetary exploration, we have designed an adaptable lunar nanosatellite which leverages several new technologies such as 3-D printed construction, photonic integrated chips, a miniaturized optical communication package, and a novel Iodine plasma thruster. Saberwing will analyze the lunar surface with a thermal and multispectral imager, demonstrating planetary exploration from a nanosatellite/CubeSat platform. Currently planned for launch in mid-2018, success of Saberwing will show that interplanetary spaceflight can be conducted at a low cost and without the need of a primary interplanetary parent craft.

G.5 Managing Thermal Requirements of a CubeSat System

Sydney Nugent Pierce
(MilesSpace)

Thermal management is one of many technical challenges faced by the Team Miles CubeSat entry in the NASA CubeQuest Challenge Deep Space Derby. After launch, the spacecraft would be dropped off just beyond the Moon. Over the the course of 200 days, it would travel at least 4 million km from Earth toward Mars, experiencing temperatures ranging from about double room temperature at mission start to slightly above freezing at mission end. The crafts thermal environment would be affected by orientation with respect to the Sun, power consumption, energy loss through plasma kinetic energy, and radiated RF energy. The key to successful thermal management may lie in orchestrating a successful interplay of craft structure, component heat requirements, and timing. The proposed solution incorporates craft motion, material selection, coatings, components, and speed. The solution also includes distributing heat around the craft, delivering heat where it is most useful, and dissipating it when and where it reaches harmful levels.

G.6 Flexible Flight Software Framework Facilitating Evolving Devices and Interfaces

Douglas Forman, Craig Pires, Scott Christa, and Michael Logan
(NASA Ames Research Center)

Smallsat and Cubesat missions are often on the cutting edge, using new technology with limited flight heritage. Mission science objectives are constantly pushing new advances in payload instrumentation (i.e. spectrometer instruments, biology experiments, laser communication demonstrations). Also, newly developing commercial general-purpose spacecraft technologies are often selected for cost savings measures (i.e. BCT XACT, MMA Solar Array Gimbals, Iris Deep Space Transponder)

These newly developed payload and spacecraft hardware devices are often not available until late in the game and usually in limited quantities. Also, hardware devices (for example Star Tracker, IMUs, Reaction Wheels) usually can't be used in an earth-based test-like-you-fly manner to test modes and transitions of closed loop controllers. In addition, sensor, actuator and payload devices usually can't be configured to produce the different combinations of outputs needed to test on-board fault management software.

To reduce risk of the limited and/or late availability of hardware devices, along with the need to simulate device behavior for closed-loop and fault injection scenarios, a flexible Flight Software Framework derived from the LADEE Flight Software Framework has been used for Flight Software Development on the BioSentinel project. This framework contains the following features:

- Core Flight Executive (cFE) Loosely-Coupled App-based Publish/Subscribe Infrastructure for both on-board and real-time simulation software.
- Control System code and associated plant (sensor/actuator) software developed in Simulink with embedded cFE apps auto-generated from models
- Requirements Verified with Test Scenarios performed on Closed-Loop Processor/Hardware in the Loop Simulators
- Hardware Transport Mechanisms abstracted as standard Posix I/O device drivers
- Hardware Transports emulated with various levels of fidelity (UDP, RS422, SPI, SpaceWire) and configured for various testing perspectives.
- App-to-App, device-to-Bus, and Space-to-Ground Cmd/Tlm Interfaces defined in configuration controlled Django-based Database
- Cmd/Tlm interface code (on-board and ground) generated from database queries.
- Inexpensive Binary-Compatible soft-core (FPGA-based) LEON Software Development Units
- Early deliveries of inexpensive soft-core Development Units from Transponder and Spacewire Interface hardware.

This presentation will describe how these features are combined to facilitate development of BioSentinel Flight Software and System Level Testing in concert with the evolving development of various external hardware devices.

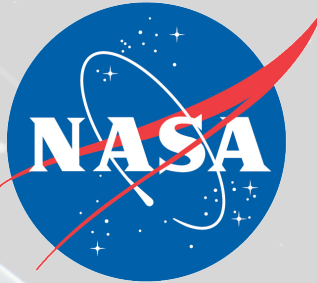
9. Social Program

Dinner Reception (May 1st)

Dinner is included in the cost of registration for all conference attendees at 6:00 pm on Monday, May 1st in Meeting Room 4 on the upper level of the San José State University Student Union. Meals can also be purchased for guests of attendees. All participants are encouraged to attend!

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