

<b>Tuesday, May 29th</b>		
<b>Time</b>	<b>Event</b>	<b>Speakers</b>
13:00	Registration opens	
14:00-14:10	Welcome address	Alessandra Babuscia (MIT) and Michael Johnson (Cornell/JA)
14:10-14:40	Keynote	K.1.1 Space technology At NASA: Breadth, Depth, and a Small-Satellite Strategy, Mason Peck (NASA/Cornell)
14.40-15.55	A.1 - Technology: System Issues for Interplanetary CubeSat Missions	A.1.1 Interplanetary CubeSat Architecture and Missions, Robert Staehle, JPL
		A.1.2 Identification and Evaluation of iCubeSat Mission Architectures, Mathew Zwack, Georgia Institute of Technology
		A.1.3 Interplanetary CubeSat System Design Challenges and Architectures, Austin Williams, Cal Poly
		A.1.4 A Cost Estimating Methodology for Very Small Satellites, Mary Boghosian, Aerospace Corporation
		A.1.5 Understanding Technology S-Curve's in The Exploration of The Solar System, Sean Murphy, Draper Laboratory
15:55-16:10	Q&A for speakers of A.1	Moderators: Michael Johnson (Cornell/JA) and Alessandra Babuscia (MIT)
16.10-16.20	Coffee Break	
16.20-17.50	A.2 - Technology: Communications, Planning, Operations, and Computing Issues for Interplanetary CubeSat Missions	A.2.1 Increasing Interplanetary CubeSat Mission Science Return with Model Based Transmission Reduction, Jeremy Straub, University of North Dakota
		A.2.2 Inflatable Antenna for CubeSat: Motivation for Development and Initial Trade Study, Alessandra Babuscia, MIT
		A.2.3 Simulating Delay Tolerant Networking for CubeSats, Paul Muri, University of Florida
		A.2.4 Optimal Operations Planning for Interplanetary Small Satellite Exploration Missions Applied to a Phobos Lander Mission, Sara Spangelo, University of Michigan
		A.2.5 Operational Considerations for CubeSats Beyond Low Earth Orbit, E. Glenn Lightsey, The University of Texas at Austin
		A.2.6 Distributed Computing on Cubesat Clusters using MapReduce, Obulpathi Challa, University of Florida
17.50-18:10	Q&A for speakers of A.2	Moderators: Mary Knapp (MIT) and Rodrigo Zeledon (Cornell)
18.15-19.15	MIT and Space Systems Lab (SSL) tour	
19:20-21:00	Dinner reception in E14 MPR-674	

<b>Wednesday, May 30th</b>		
8:30-9:00	Breakfast	
9:00-9:30	Keynote	K.1.2 Planetary Science in an iCubeSat Era Sara Seager, MIT, Prof. Physics and Planetary Science
9:30-10:45	B.1 – Science: Interplanetary CubeSat Missions and Science	B.1.1 Scouting Saturn’s Rings with Small Spacecraft, Matthew Hedman, Cornell University
		B.1.2 Open Questions in the Outer Solar System: CubeSat/ChipSat Opportunities, Matthew Tiscareno, Cornell University
		B.1.3 LunarCube: Updating the CubeSat Standard to Support Cis-Lunar Missions, Pamela Clark, Catholic University of America
		B.1.4 Preliminary Design of Very Small Satellites for Venus Reentry, Derek Dalle, University of Michigan
		B.1.5 ChipCube: an Open Source Open Access Generic Planetary Science and Exploration System, Michael Johnson, Cornell University / JA
10:45-11:05	Q&A for speakers of B.1	Moderators: Lorraine Weis (Cornell) and Rebecca Jensen-Clem (MIT)
11:05-11:15	Coffee break	
11:15-12:30	B.2 – Science: Technologies and Missions to Enhance Interplanetary CubeSat Science	B.2.1 Interplanetary Radio Occultation CubeSat Constellation, Kerri Cahoy, MIT
		B.2.2 Enhancing Radio Science Missions with CubeSats, Kamal Odurhiri, MIT
		B.2.3 HiMARC 3D- High-speed, Multispectral, Adaptive Resolution Stereoscopic CubeSat, Ved Chirayath, Stanford University
		B.2.4 Nanosatellite for Earth Environmental Monitoring: The MICROMAS Project, William Blackwell, MIT Lincoln Laboratory
		B.2.5 The Phoenix Program: CubeSats as an Option for Repurposing Geostationary Assets, Jaime Ramirez-Riberos, Aurora Flight Sciences
12:30-12:50	Q&A for speakers of B.2	Moderators: Rodrigo Zeledon (Cornell) and Alessandra Babuscia (MIT)
12:50-13:35	Lunch	
13:35-14:35	C.1 – Technology: Propulsion Issues for Interplanetary Cubesat Missions	C.1.1 Ion Drive Interplanetary CubeSat Carl Brandon, Vermont Technical College
		C.1.2 Ion Electro Spray Thruster Assembly for CubeSats, Francois Martel, Espace Inc.
		C.1.3 ESTCube-1: Stepping Stone for Fast Interplanetary Travel, Mart Noorma, University of Tartu
		C.1.4 E-Sail Test Mission: Reaching the Solar Wind With a CubeSat, Jouni Envall, Finnish Meteorological Institute
14:35-15:20	C.2 – Technology: Propulsion Issues and Launching Capabilities for Interplanetary CubeSat Missions	C.2.1 ULA Rideshare with CubeSat Missions for Lunar and Planetary Exploration Jake Szatkowski, United Launch Alliance
		C.2.2 NanoTHOR and PowerCube: Affordable Launch and Propulsion for Deep-Space CubeSats, Robert Hoyt, Tethers Unlimited Inc.
		C.2.3 High Delta V Propulsion for CubeSats, Vlad Hruby, Busek
15:20-15:45	Q&A for speakers of C.1 and C.2	Moderators: Sara Spangelo (U. Michigan) and Mary Knapp (MIT)

15:45-16:05	Coffee break	
16:05-16:20	Planetary Resources Q&A	Moderators: Mary Knapp (MIT) and Alessandra Babuscia
16:20-17:35	C.3 – Technology: Navigation, Control, Tracking, and Formation for Interplanetary CubeSat Missions	C.3.1 A Novel Hemispherical Anti-Twist Tracking System for CubeSat Applications (CubeHATTS), Eli Bashkevin, Stanford University
		C.3.2 Low Mass Radio Science Transponder- Navigation Anywhere, Courtney Duncan, NASA-JPL-Caltech
		C.3.3 The MotherCube Distributed Architecture for CubeSat Cluster Missions, Justin McClellan, Aurora Flight Sciences
		C.3.4 The Location-Scheduled Control Architecture as Applied to Interplanetary CubeSats, Matthew Sogenfrei, University of California Davis
		C.3.5 Attitude Control System for Arc-Second Stabilization of 30Kg Micro Astronomy Satellite, Takaya Inamori, The University of Tokyo
17:35-17:50	Q&A for speakers of C.3	Moderators: Rebecca Jensen-Clem (MIT) and Michael Johnson (Cornell/JA)
17:50-18:00	Closing remarks	Michael Johnson (Cornell) and Alessandra Babuscia (MIT)
1800-18:30	Exhibition breakdown	
20:00	Informal dinner in Boston	
<b>Ongoing</b>		
Poster Session		P.1.1 Real-Time Attitude-Independent Three-Axis Magnetometer and Gyro-Bias On-orbit Calibration for Pico-satellites, Tian Xiang, Zhejiang University
		P.1.2 UPPESAT: Seismic Activity Determination Nanosatellite, Samaksh Behl, University of Petroleum and Energy Studies
		P.1.3 A CubeSat-based Science Mission for Meteor Research, Ryo Ishimaru, Chiba Institute of Technology
		P.1.4 Nano-habitats: Advance CubeSats to improve Design and Construction of HSF Hardware, Raul Polit-Casillas, JPL
		P.1.5 A New Sesnsor Platform for the Interplanetary CubeSat Missions Sanjay Srikanth Nekkanti, Lulea University of Technology
		P.1.6 Active Pointing, on a Budget Aaron Goldstein (Sun Devil Satellite Laboratory)

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## 2. Welcome

The iCubeSat Organizing Committee welcomes you to the first Interplanetary CubeSat Workshop, which will address the technical challenges, opportunities, and practicalities of space exploration with CubeSats. The workshop will provide a unique environment for open practical collaboration between academic researchers, industry professionals, policy makers, and students developing this new and rapidly growing field.

## 3. Contacts and Hours

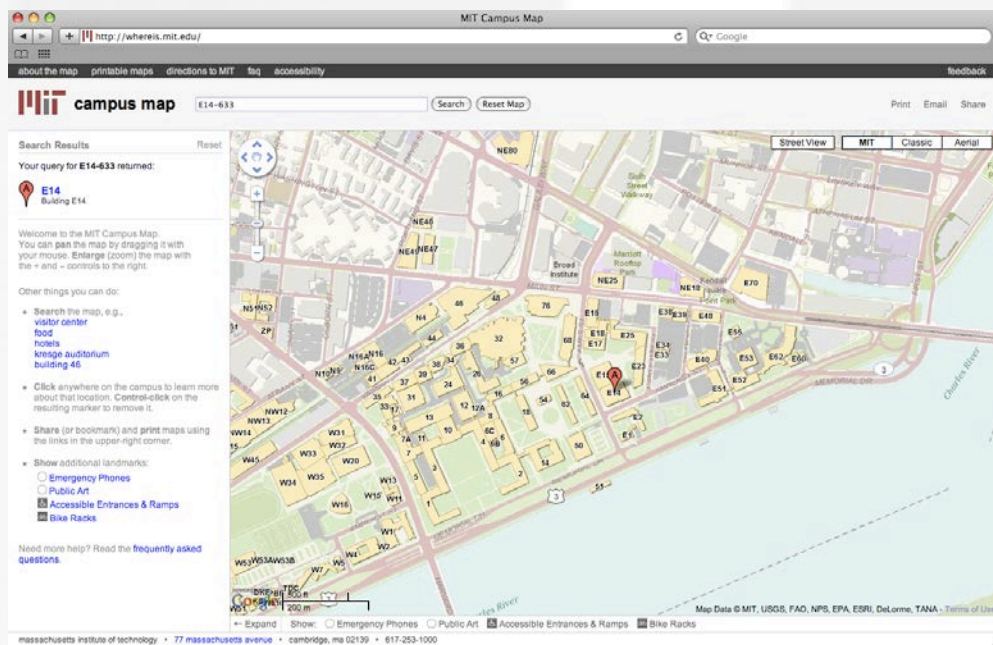
The registration desk will be open from 12:00-6:00pm on May 29<sup>th</sup> and from 9:00am-3:00pm on May 30<sup>th</sup>.

Please don't hesitate to contact the iCubeSat committee at [committee@icubesat.org](mailto:committee@icubesat.org) at any time during the conference.

## 4. Location and Venue

All conference talks are held in room **E14-633**, on the 6<sup>th</sup> floor of the MIT Media Lab. Conference exhibitors, posters, and the satellite talk-viewing venue are located across the hall in **E14 MPR-674**.

A Google Maps version of the MIT map can be found here: <http://whereis.mit.edu/>



## 5. Organizing Committee

<b>First Name</b>	<b>Last Name</b>	<b>Affiliation</b>
Alessandra	Babuscia	MIT
Rebecca	Jensen-Clem	MIT
Michael	Johnson	Cornell University / JA
Mary	Knapp	MIT
Sara	Spangelo	University of Michigan
Lorraine	Weis	Cornell University
Rodrigo	Zeledon	Cornell University

## 6. List of Exhibitors and Booth Map

Aeronautical and General Instruments Limited (AGI)  
Busek Co. Inc.  
Comtech AeroAstro  
Draper Laboratory  
JA  
Journal of Small Satellites (JoSS) Online  
Micro Aerospace Solutions  
MIT Department of Aeronautics and Astronautics  
MIT Department of Earth, Atmospheric, and Planetary Science  
Sinclair Interplanetary  
Stanford University Space Systems Development Laboratory (SSDL)  
United Launch Alliance (ULA)



## 7. Keynote Speaker Biographies

### Mason Peck – NASA Chief Technologist



On Jan. 1, 2012, Cornell University Professor Mason Peck became NASA's chief technologist. Peck will serve as the agency's principal advisor and advocate on matters concerning technology policy and programs. As the chief technology advocate, Peck will help communicate how NASA technologies benefit space missions and the day-to-day lives of Americans. Peck serves as NASA's chief technologist through an intergovernmental personnel agreement with Cornell, where he is on the faculty as an associate professor in the School of Mechanical and Aerospace Engineering and teaches in Cornell's Systems Engineering Program. He has a broad background in aerospace technology, which comes from nearly 20 years in industry and academia. Prior to his NASA appointment, Peck also worked as an engineer and consultant with industry and organizations including Boeing, Honeywell, Northrop Grumman, Goodrich and Lockheed Martin. At Cornell, Peck's work focuses on spacecraft dynamics, control and mission architectures. Some of this research includes micro-scale flight dynamics, gyroscopic robotics, and magnetically controlled spacecraft, most of which have been demonstrated on NASA microgravity flights. He has been the P.I. for two nanosatellites, CUSat and Violet, which are anticipating launches in 2012-2013. Peck earned a doctorate in aerospace engineering from the University of California, Los Angeles as a Howard Hughes Fellow and a master's degree in English literature from the University of Chicago.

### Sara Seager – MIT Professor of Planetary Science and Physics



Science and Professor of Physics at MIT. Before joining MIT in 2007, she spent four years on the senior research staff at the Carnegie Institution of Washington preceded by three years at the Institute for Advanced Study in Princeton, NJ. Her PhD is from Harvard University and her BSc in math and physics from the University of Toronto. Professor Seager's research focuses on theoretical models of atmospheres and interiors of all kinds of exoplanets. Her research has introduced many new ideas to the field of exoplanet characterization, including work that led to the first detection of an exoplanet atmosphere. She was part of a team that co-discovered the first detection of light emitted from an exoplanet and the first spectrum of an exoplanet.



## **8. Conference Abstracts**

### **Session K – Keynote Speakers**

#### **K.1 Space Technology At NASA: Breadth, Depth, and a Small-Satellite Strategy**

Mason Peck (NASA/Cornell)

NASA's new Space Technology Program has funded more than 1,000 projects since its inception in 2011. These projects span the entire spectrum of technology readiness - from early-stage concepts to flight-demonstration hardware that will enable our future missions. Several new programs at NASA within Space Technology offer funding opportunities for innovators across the nation to develop small-satellite technologies: ELaNa, which provides launch opportunities for CubeSats; Edison, which provides significant funding for in-orbit technology demonstrations; and a suite of early-stage innovation and game-changing development programs. In particular, the Edison SmallSat program helps to continue America's leadership in space through the further development of this class of satellites--small, agile and relatively inexpensive spacecraft that could perform many tasks in science, exploration, operations, and commercial development of space in a way that has not been seen before. These spacecraft represent a new opportunity for NASA to approach its diverse goals in science, exploration and education. Encouraging the growth of small-spacecraft technology also benefits our economy. Many of the technologies that enable small spacecraft come from the innovative world of small business, where commercial practices provide innovative and cost-effective solutions. Those technologies will continue to advance in performance as demand and competition drive companies to excel.

## K.2 Planetary Science in an iCubeSat Era

Sara Seager (MIT)

Planetary science is the study of planets, moons, and planetary systems. Even after decades of study and spacecraft visits, lofty science goals remain. Arguably the most exciting goal is the search for signs of past or present life on the surface or subsurface of a handful of solar system planets and moons. Of equal interest is asteroid characterization for future resource extraction. The newest field of planetary science is the discovery and characterization of exoplanets, planets orbiting stars other than the sun. While big NASA missions are becoming cost-prohibitive, the rise of CubeSats suggests a possible new paradigm with frequent launches of highly specialized small missions. The question remains as to whether big science can fit within a small package—namely the power, mass, volume, and data limitations. I will discuss which planetary science goals for which solar system bodies are not only reachable but suited to iCubeSat-type of missions.

## Session A.1 – Technology: System Issues for Interplanetary CubeSat Missions

### A.1.1 Interplanetary CubeSats: Some Missions Feasible Sooner than Expected

Robert Staehle (Jet Propulsion Laboratory, California Institute of Technology), Jordi Puig-Suari (CalPoly SLO), Tomas Svitek (Stellar Exploration), Louis Friedman (The Planetary Society), Diana Blaney (JPL-Caltech)

NASA's Innovative Advanced Concepts (NIAC) program selected Interplanetary CubeSats for further investigation, some results of which are reported. Interplanetary CubeSats enable small, low-cost missions beyond LEO. This class is defined by mass  $< \sim 10$  kg, cost  $< \$30$ M, and durations up to 5 years. Over the coming decade, a stretch of six distinct technology areas, creating one overarching architecture, can enable comparatively low-cost Solar System exploration missions with capabilities far beyond those demonstrated in small satellites to date.

Technologies:

1. CubeSat electronics and subsystems extended to operate in the interplanetary environment (esp. radiation and duration of operation).
2. Optical telecommunications to enable very compact, low power uplink/downlink over interplanetary distances.
3. Solar sail propulsion to enable major maneuvers and rendezvous with multiple targets using no propellant.
4. Navigation of the Interplanetary Superhighway to enable multiple destinations over reasonable mission durations with achievable delta-V.
5. Small, highly capable instrumentation (such as a miniature imaging spectrometer) enabling acquisition of high-quality scientific and exploration information.
6. Onboard storage and processing of raw instrument data and navigation information to enable maximum utility of uplink and downlink telecom capacity, and minimal operations staffing.

When integrated, these technologies form the Interplanetary CubeSat Architecture.

Architecture: Interplanetary CubeSats build on the existing Earth-orbiting CubeSat architecture. Target spacecraft volume is 10 cm x 20 cm x 30 cm (6U). 2U are reserved for the mission-specific payload. The solar sail occupies 2U and deploys to form a 6 x 6 m or larger square. The solar sail is

based on the Planetary Society/Stellar Exploration LightSail™ 1, plus electrochromic tips for attitude control. A 2-way optical communication terminal occupying 1U is based on JPL laser telecommunications developments, with a link capacity of 1 kbps @ 2 AU Earth-spacecraft distance. The final 1U is used for satellite housekeeping (C&DH, power, attitude determination) and based on CalPoly CP7 and JPL CubeSat On-board processing Validation Experiment (COVE) avionics.

Candidate missions: Though there are many different missions that would be possible with this architecture, the potential missions being researched under NIAC sponsorship are:

1. Mineral Mapping of Asteroids
2. Solar System Escape Technology Demonstration
3. Earth-Sun Sub-L1 Space Weather Monitor
4. Phobos Sample Return
5. Earth-Moon L2 Radio Quiet Observatory
6. Out-of-ecliptic Missions

Objectives and technology drivers of these missions are reported to illustrate the broad spectrum of missions enabled by advancing the CubeSat state-of-the-art beyond low Earth orbit.

## **A.1.2 Identification and Evaluation of iCubeSat Mission Architectures**

Mathew Zwack, Stephen Edwards, Jonathan Sharma, Chris May,  
and Dimitri Mavris (Georgia Institute of Technology)

Since the genesis of the CubeSat standard, the usage of CubeSats has become increasingly popular in commercial, military, and academic applications alike. CubeSats typically serve as cost effective test-beds and demonstrators for various in-space technologies in earth orbit. However, their low cost paradigm is beginning to extend into many other areas of satellite operations. With the advent of new technologies, the use of CubeSats for missions extending far beyond earth orbit can be realized. The first step towards the realization of interplanetary CubeSat (iCubeSat) missions is the identification and evaluation of candidate mission architectures. The idea of an iCubeSat is relatively new and it is, therefore, important to evaluate as many mission architectures as possible while avoiding the use of historical experience as a down-selection tool. This study uses various pre-conceptual level systems engineering techniques to identify and evaluate candidate architectures for a general iCubeSat mission. The architectures are assembled using a Morphological Matrix of Alternatives (MoA), and are then evaluated against a list of attributes using an Analytical Hierarchy Process (AHP). Application of AHP allows for the use of qualitative data in performing a quantitative assessment, enabling a rapid evaluation of all the possible mission architectures that can be defined by the MoA. From this analysis, the Pareto optimal solutions are identified, providing insight into the driving trades that exist for the novel concept of iCubeSat missions. A method for identifying candidates from the Pareto optimal solutions for further study is presented using Multi-Attribute Decision Making (MADM) techniques to rank the architectures based upon a prioritization of mission objectives.

### **A.1.3 Interplanetary CubeSat System Design Challenges and Architectures**

Austin Williams (Cal Poly)

The desire to utilize low cost, quick turn around CubeSats for interplanetary missions is an exciting challenge. There are three fundamental constraints to the system design that a long duration, interplanetary mission imposes: Power Generation, Volume, and Radiation. This talk will discuss the critical design decision between going RadHard vs COTS, and provide a comparison of their relative performance, and power requirements. A brief discussion on radiation effects on components will lead into a trade of several system architectures. It will be shown that the pace that modern mobile electronics are progressing, and performance per watt that they achieve makes a strong case for their utilization. Modern processors and memory provide the processing capability and storage, with a variety of "Sleep" modes for significant power savings. Several radiation tolerant system design techniques are discussed to enable COTS technology to survive long duration, interplanetary missions. The talk will end by proposing a mission that could provide enormously useful data points that can influence the design of technically ambitious CubeSat missions with high science value.

## **A.1.4 A Cost Estimating Methodology for Very Small Satellites**

Mary Boghosian and Ricardo Valerdi (Aerospace Corporation)

This presentation summarizes an internal research and development effort at The Aerospace Corporation (Aerospace) to create a methodology for estimating the cost of very small satellites, including picosats and CubeSats. Costing methodologies for picosatellites are of particular interest due to the fact that none of the currently available cost methodologies are applicable to this range of satellites, yet the capabilities of smaller satellites are advancing, and their production and launch frequencies are increasing. We at Aerospace Corporation have realized this need and have engaged in developing a cost methodology to cover the small satellite mass range (<50kg-0.1kg). Through literature search and interviews with subject matter experts involved in the development of small satellites, we derived a new approach for costing. We named this new approach the Aerospace Picosatellite COst MOdel (A-PICOMO). This new methodology required development of Cost Drivers unique to very small satellites and the validation of the drivers with historical data from completed picosat projects. We identified and defined two categories of cost drivers, System Size Drivers, and System Cost Drivers or (Project Drivers) that help characterize the complexity and cost of picosats. In addition to describing the results of our research, we will describe our approach in developing the new cost methodology and the outcome of our initial validation. This presentation will also discuss observations and lessons learned in costing such small satellites.

## A.1.5 Understanding Technology S-Curves in The Exploration of the Solar System

Sean Murphy (Draper Laboratory)

Interplanetary exploration has been one of NASA main mission objectives since the early seventies, from fly-by probes, landers and rovers. Billions of dollars have been invested into the technology and infrastructure to provide in-situ sensing from other planets as well as close up remote sensing with various instruments. This infrastructure and industrial base has been developed during the cold-war and has all the trappings of it, large scale programs with standing armies of engineers. It has provided incalculable benefits in terms of technology development and scientific research.

However, our early gains in science and exploration has been slowing down due maturity of the market and technology. The technology S-curve is often used to predict the likelihood of an emerging technology is to supplant an established one. The talk will focus on understanding where are the current missions on the technology S-curve, (low, medium, high) and more importantly what are the emerging technologies which could disrupt the current market and drastically change it.

This complex issue is at a heart of our space technology development cycles which will drive the direction of space exploration for the next thirty years. Understand this critical issue will help NASA, Universities, NGO's, and the private sector to make better decisions and how to better utilize their resources for the exploration of our solar system and training the next generation of scientist and engineers.



## **Session A.2 – Technology: Communications, Planning, Operations, and Computing Issues for Interplanetary CubeSat Missions**

### **A.2.1 Increasing Interplanetary CubeSat Mission Science Return with Model Based Transmission Reduction**

Jeremy Straub (University of North Dakota)

An interplanetary CubeSat faces a fundamental communications problem. Given its small size, it must use a lower transmission rate (compared with larger interplanetary spacecraft) in order to achieve reliable communications with an Earth-based ground station. However, the reduction of the transmission rate dramatically decreases the amount of scientific data that can be sent back to Earth. While there are clearly ways to increase the effective data transfer rate somewhat (e.g., expandable antennas, increasing ground receiver gain, compression, etc.) it is likely that the CubeSat will generate significantly more data than it can send. This is, of course, highly problematic as the science return for missions conducted under the prevailing communications model is clearly a function of the scientific data returned to Earth.

This paper proposes and evaluates a new paradigm for increasing mission science return as a function of data transfer. Instead of transmitting raw data, the proposed approach begins with the creation of a model (either mission specific, or quasi-generic) that is then evaluated in-situ by the spacecraft. The craft control software directs the collection of data that serves to validate or refute the model. This data is evaluated onboard and elements of the model are deemed to be validated or refuted (with an associated level of confidence). Model updates, validation confidence reports and supporting data for both are then sent over the limited communications link to ground controllers and Earth-based scientists for review and further analysis. Depending on the accuracy of the original model and the relative size of model-messages versus the data that must be transmitted in raw form for their creation, the data transmission savings could be several orders of magnitude.

This paper presents a detailed overview of the proposed approach, the application of both Dempster-Shafer and classical probability to model confidence characterization and an evaluation of the proposed approach in the context of the transmission of planetary science data. It demonstrates an analytical method for characterizing the decreased data transmission requirements and increased science returns possible. It also comments,

qualitatively, on the mission concept possibilities facilitated by the proposed approach – specifically focusing on greater-distance-from-Earth missions.

## **A.2.2 Inflatable Antenna for CubeSat: Motivation for Development and Initial Trade Study**

Alessandra Babuscia, Mark Van de Loo, Mary Knapp, Rebecca Jensen-Clem, Sara Seager (MIT)

CubeSat and small satellites are becoming a way to explore space and to perform science in a more affordable way. As the goals for these spacecraft become more ambitious in space exploration, moving from Low Earth Orbit (LEO) to Geostationary Earth Orbit (GEO) or further, the communication systems currently implemented will not be able to support those missions. One of the bottlenecks in small spacecraft communication systems is represented by antennas, due to the close relation between antenna gain and dimensions. Current antennas for CubeSat are mostly dipole or patch antennas with limited gain. Deployable (not inflatable) antennas for CubeSat are currently being investigated, but these solutions are affected by the challenge of packaging the whole deployable structure in a small spacecraft. The work that we propose represents the first attempt to develop an inflatable antenna for a CubeSat. Inflatable structures and antennas can be packaged efficiently occupying a small amount of space, and they can provide, once deployed, large dish dimension and correspondent gain. Inflatable antennas have been previously tested in space (Inflatable Antenna Experiment, STS-77). However they have never been developed for small spacecraft such as CubeSat, where the packaging efficiency, the deployment, and the inflation represent a challenge.

The article is structured as follow: context and benefits of using inflatable antennas are described; then a trade study to design the antenna which maximizes performance while respecting CubeSat constraints is presented.

### A.2.3 Simulating Delay Tolerant Networking for CubeSats

Paul Muri and Janise McNair (University of Florida)

Delay Tolerant Networking (DTN) is a networking protocol suite addressing many of the communication challenges CubeSats encounter with space exploration including low transmission power, intermittent connectivity, long delay, and high bit error rate. DTN protocols have been successfully tested for space communication on larger spacecraft such as the International Space Station, Epoxi, Earth Observing-1 satellite, IntelSat 14, and UK-DMC. For CubeSats, a DTN convergence layer adapter has been implemented for the popular link layer protocol AX.25. Most research for DTN space communication relies on simulation to validate protocols since real deployments are often either very expensive or impossible. The effectiveness of DTN simulators for space internetworking is sensitive to the level of realism. Many DTN simulators do not currently implement a realistic physical model or networking stack. There is also an issue of cross-simulator comparability. Researchers often create their own simulators to test algorithms, so it can be difficult to compare a new algorithm with existing ones unless the new protocol is implemented on a variety of simulators.

In this paper we describe a virtual space-internetworking environment to control test bed nodes of Linux-based and smart phone-based hardware candidates for CubeSats. To simulate we created a DTN module in Network Simulator 3 (NS-3), a widely available and capable open-source simulator. Our module simulates physical DTNs up to the data link layer as WiFi-type, including topology and mobility patterns, ranges, rates, and error characteristics. For the networking stack's higher layers, the module adds connections to nodes, external to NS-3, and may be virtual machines, Linux containers, or external hardware nodes. Hardware nodes in the form of laptops, routers, and smart phones were used because these are the best candidates for an experimental payload for CubeSats.

For experimentation on our platform, we developed mobility models such as low-earth orbiter to ground station, and interplanetary CubeSat clusters. We evaluated the models using DTN metrics of data-rate, bundle-drop ratio, overhead, and transmission window time. When compared with UDP/IP, the DTN metrics outperform with higher data-rate, lower bundle-drop ratio, less overhead, and longer transmission windows for the given mobility models. Thus, this flexible and scalable simulation platform emulates DTN networking performances for various space topologies on CubeSat hardware candidates. The outcomes are internetworking solutions that overcome CubeSat communication limitations for space exploration.

## **A.2.4 Optimal Operations Planning for Interplanetary Small Satellite Exploration Missions Applied to a Phobos Lander Mission**

Sara Spangelo and James Cutler  
(University of Michigan)

Interplanetary missions face significant operational challenges due to the constraints on available energy, often unstable orbital properties, and the difficulty in the communicating command and mission data at great distances from the Earth. Operations are increasingly complex due to the stochastic environments of interplanetary space. For example, gravity and atmospheres at interplanetary bodies may be poorly understood, impacting the orbits and in turn the opportunities for the satellite to collect energy and data and communicate. Planning interplanetary missions is increasingly complex since they often have multiple objectives, for example maximizing science return while minimizing risk of failure. Thus, there is the need for modeling, analysis, and optimization tools to design feasible and robust operational schedules which can be executed autonomously for interplanetary exploration.

This paper uses a generic, analytic modeling framework for optimizing the operations of interplanetary spacecraft mission architectures. The framework may be applied to distributed networks with diverse communication nodes, including orbiters and/or landers in mothership-daughtershp architectures, and Earth-based ground stations.

We apply our modeling framework to develop optimal operational schedules for a novel science mission designed to investigate Phobos by maintaining its position at the Lagrange point between Mars and Phobos. The architecture consists of a mothership that orbits Mars and a secondary small craft that lands on Phobos. We model realistic orbital mechanics and consider opportunities to collect energy from the sun and communicate and relay information back to the Deep Space Network (DSN) via a mothership. The operational decisions include the data rates for communication from the lander to the mothership and the data rates for communication from the mothership to the DSN, and the operational and communication schedule. Constraints on available energy, available data, storage constraints, and opportunities to perform operations are considered. There are multiple objectives and constraints in this problem, for example maximizing the science returns of the mission while maximizing schedule robustness to manage mission uncertainty. We explore both simple heuristic approaches, which may be useful for autonomous operations, and multi-objective formulations in our optimization examples.

Results are provided for the proposed Phobos mission architecture. We investigate the sensitivity of the optimal design solutions to model uncertainty, such as the accuracy of the landing site and knowledge of power generation. The general model and optimization formulation presented in this paper can be applied to a broad class of interplanetary and near-Earth missions.

## A.2.5 Operational Considerations for CubeSats Beyond Low Earth Orbit

E. Glenn Lightsey (The University of Texas at Austin)

The CubeSat standard has created a wide range of new opportunities for access to space. Leverage of Commercial Off The Shelf (COTS) technology has made a number of lower cost missions possible that would have been cost prohibitive a decade ago. An important new class of potential missions for CubeSats is possible outside of Low Earth Orbit (LEO). While the potential is great, such Deep Space CubeSat missions must account for the different environmental and operational factors in higher altitude Earth orbits and interplanetary space. This presentation explores three spacecraft design issues that must be addressed with regard to operation in deep space. These topics are: radiation, guidance and control, and communications.

The radiation environment is significantly more severe in deep space. This consideration affects the survivability of COTS electronics with respect to single event effects and life expectancy. The first part of this presentation includes a comparison of the relative radiation environments of different types of orbits (LEO, high altitude Earth orbit, and interplanetary). A description is provided of how these environments affect electronics, what mitigation steps are possible, and their relative implementation costs.

Guidance and control is another design element that is impacted by operating environment. The set of sensors and actuators that will work for both attitude and position control is more limited than what is available in Earth orbiting missions. This design trade space will be examined with some comments on what is perceived to be available at the current state of the art.

The final consideration in this presentation is communications. CubeSats present unique design challenges due to their smaller size and limited available power. Communications, both in the ability to establish a two way link and in the amount of data that can be transmitted, is an issue for deep space missions. A basic analysis will be conducted as well as a presentation of some operational solutions.

## A.2.6 Distributed Computing on CubeSat Clusters using MapReduce

Obulapathi N. Challa and Dr. Janise McNair (University of Florida)

Weight, volume, dimensions and power generation capabilities of a CubeSat are constrained to 1000 grams, 1 liter, 10 x 10 x 10 cm cubed and 2.5 watt respectively. These constraints severely limit storage, processing and communication capabilities of individual CubeSats. A typical CubeSat has about 1 GB memory, 25 MIPS @ 25 MHz processing capability and 9.8 Kbps communication capability. Emerging applications for CubeSats, such as remote sensing, will require more of storage, processing and communication capabilities. For interplanetary CubeSat missions the above constraints pose even more problems as the connectivity with ground station will be very limited, intermittent and comes at a very high price. This paper proposes Cubesat MapReduce(CMR), using which processing resources can be pooled among CubeSats in a cluster to speedup missions that require processing of image, video and other multimedia data.

Inspired by map and reduce primitives from Lisp, Google introduced MapReduce framework which is now being widely used for processing vast amounts of data in parallel on large clusters of compute nodes. Map takes a function and a sub-problem as input and applies the function to the sub-problem to generate a sub-solution. Reduce stitches these sub-solutions into full solution.

Each CubeSat cluster has a master node which orchestrates CMR. All CubeSats in the cluster, other than the master, are pooled to form a worker pool. Master node splits the data set to be processed into large number of fixed size blocks called chunks. Chunks are distributed and scheduled for execution on worker nodes to generate sub-solutions. As and when worker nodes finish jobs, new jobs are assigned. Once all the chunks are processed, the sub-solutions are sent to the master node which stitches them together.

We simulated CMR using CubeNet, a Python based CubeSat cluster simulator. Our simulations indicate that CMR, with cluster sizes in range of 5-25 CubeSats, can process images and videos at about 4-20 times faster than an individual CubeSat with a power overhead of 250 mW/node/Mb (cluster size of 5) to 140 mW/node/Mb (cluster size of 25). CMR has a negligible memory overhead (< 0.01%) to store metadata. These results indicate that CMR can speedup image and video processing missions by a factor of 4-20x. Future work will include distributed Reduce operation and integration with cluster based distributed file systems along with locality optimization to improve the scalability and power efficiency of CMR.



## Session B.1 – Science: Interplanetary CubeSat Missions and Science

### B.1.1 Scouting Saturn's Rings with Small Spacecraft

Matthew Hedman, Matthew Tiscareno, Joseph Burns, Philip Nicholson, and Michael Johnson (Cornell University)

Large numbers of small spacecraft could provide powerful new ways to explore Saturn's dense Main Rings at close range. While these rings span a region several hundred thousand kilometers wide, they are composed of particles that are only millimeters to meters across. These ring particles move around the planet at roughly 20 km/s, but the relative speeds of nearby ring particles are only about 1 mm/s. Mutual gravitational attraction and frequent collisions among these ring particles produce diverse structures on a wide range of spatial scales. Saturn's Main Rings therefore provide a natural laboratory for investigating the dynamics of particle-rich disks. However, obtaining data on the rings at the size scale of individual particles is challenging because it is difficult to approach the rings at close range without actually sending the spacecraft through the rings, where it is likely to collide with ring material. While such collisions pose a significant hazard to large spacecraft, they could also allow sufficiently rugged or disposable small spacecraft to be implanted into the rings. Once in the rings, such spacecraft could provide information about such basic parameters as the ring particles' coefficients of restitution, velocity dispersions, rotation states, and potentially even their sizes, composition and spatial distributions.

## **B.1.2 Open Questions in the Outer Solar System: CubeSat/ChipSat Opportunities?**

Matthew Tiscareno, Matthew Hedman, Philip Nicholson, Joseph Burns, and Michael Johnson (Cornell University)

The planets and moons and rings and magnetospheres of the outer solar system are rich in targets of broad interest. Yet the outer solar system is a challenging place to explore, and visits by spacecraft have been seldom compared to Mars and other inner solar system targets, partly due to high launch costs for massive payloads and high risk profiles. We will review some of the open questions in the outer solar system, some of which may be particularly amenable to investigation via a cadre of low-mass disposable spacecraft.

### **B.1.3 LunarCube: Updating the CubeSat Standard to Support Cis-Lunar Missions**

Pamela Clark (Catholic University of America), Russell Cox, Abraham Vasant, and Gregory Scharfstein (Flexure Engineering Incorporated)

We propose 'LunarCube' to extend the affordable and successful CubeSat standard to support cis-Lunar missions. Over the last decade, CubeSat has evolved in the direction those of us interested in lunar and planetary exploration would like to go: CubeSat-based programs now support cutting edge multi-institutional multi-disciplinary science using spatially and temporally distributed systems, while keeping costs low. LunarCube, analogous to CubeSat, allows higher risk implementation, thereby keeping costs low, but extends CubeSat capabilities in two stages to support operation in deep space and the lunar surface as an analog of most solar system real estate. A standard 'bus' provides standardized interfaces and shared access by guest 'instruments' to all subsystems using existing SmallSat protocols. Stage 1 would specify some additional capability in five key areas: 1) profile: somewhat longer duration (many months instead of many weeks); 2) form factor: small, but potentially larger volumes as needed; 3) control: active attitude control, propulsion; 4) information transfer: more robust, autonomous communication and C&DH systems, and 5) thermal/mechanical design: greater hardness to deep space radiation using, for example, MilSpec components, and ruggedness for extreme thermal variation. The first four would give access to lunar orbital space to provide, for example, communication satellites for cis-lunar or deep space. The fifth would allow access to, as well as survival and operation for at least a limited duty cycle on, the lunar surface. The somewhat larger volume would accommodate the additional needs, or allow several users to fly experiments. Stage 2 would enhance capability by allowing the technology impact to increase, enabling incorporation of state of the art or even currently 'under development' technologies in several key areas: 1) electronics, 2) autonomy; 3) precision navigation and control; 4) full deep cryo operation for 'cold cubes'; and 5) advanced payload integration. At this stage, 24/7 operation anywhere on the lunar surface would be possible and the LunarCube could be a virtual 'smart phone' with a 'nano-rack' representing a variety of experiments, as open access software applications. Transportation to final destination could occur either as secondary payload on larger orbiters/landers, or via the low impulse micro-thruster propulsion systems currently under development. LunarCube provides a platform that advances scientific exploration and demonstrates core technologies to support effective operation beyond Earth orbit.

## **B.1.4 Preliminary Design of Very Small Satellites for Venus Reentry**

Derek Dalle and Sara Spangelo (University of Michigan)

For planets and moons with atmospheres, the upper atmospheres are not well characterized. Better understanding of the composition and dynamics of these atmospheres may provide important insights into the formation and evolution of the solar system. Towards that goal, this paper focuses on the design of small satellites that also serve as reentry vehicles to collect and transmit sought-after scientific information. Conventional spacecraft are typically not able to collect atmospheric measurements throughout reentry due to the aerodynamic heating of the surrounding air. We propose a small satellite on a lifting reentry trajectory designed to reduce its velocity in the upper atmosphere sufficiently such that peak heating is greatly reduced and it can collect data throughout reentry.

This paper focuses on reentry for Venus towards improving the understanding of the evolution of the terrestrial planets and their atmospheres. We also expect that Venus is a feasible option for near-term interplanetary exploration. The approach developed in this paper should be applicable to other planets and moons with atmospheres.

Designing a small spacecraft to survive reentry into the atmosphere of a planet or moon involves several tightly coupled disciplines: reentry flight dynamics, aerodynamics, and thermal constraints in addition to usual small-satellite design concerns. Ideally a vehicle could, starting from a low orbit, reenter the atmosphere with gentle enough aerodynamic heating that a minimal thermal protection system would be required to ensure survivability. This has been demonstrated accidentally with unprotected debris from historical reentries such as Skylab. The key to surviving reentry is a lifting trajectory using small wing-like plates and offsetting the center of gravity of the vehicle. Such a design is subject to many uncertainties, but the low cost and high reproducibility of small satellites enables large quantities to be launched and tested with mission failures being expected and tolerable.

The ideal design optimization would aim to maximize the probability of survival based on some distribution of initial orbits and uncertainties in the vehicle design and dynamics. This initial work focuses on an important first step: designing a feasible solution for the passive reentry of a vehicle from an initial orbit, which must passively fly a trajectory that slows down enough in the upper atmosphere to avoid a damaging level of aerodynamic heating.

This study introduces a low-cost architecture to obtain useful scientific data

about upper atmospheres and reentry itself. It also investigates interesting vehicle dynamics for an atypical flight regime.

## **B.1.5 ChipCube: an Open Source Open Access Generic Planetary Science and Exploration System**

Michael Johnson  
(Cornell University / JA)

Scientific spacecraft, landers, rovers and sensor networks are typically highly optimised expensive one off designs that can only be infrequently funded by space agencies. This makes high risk or duplicate missions unpalatable and provides few opportunities for economies of scale to significantly drive down costs.

We propose a very low cost generic scientific spacecraft/lander/rover/sensor 'ChipCube' architecture based on an adaptable and modular ChipSat / CubeSat system. The system uses CubeSats to minimise launch costs and deliver swarms of ChipSat based secondary exploration systems to collect and return data for relay to earth.

The ChipSat element of the system is based around a spacecraft on-a-single-substrate (such as our gallium arsenide based GaAstroChip) that can be configured to act as part of a swarm of independent spacecraft, a lander, a limited range rover system, penetrator or a component of another exploration system. Important design assumptions include a need to support high volume low cost mass production, application dependent parametric design, a selection of integrated sensors, extensible software and hardware interfaces, infrequent low speed communications and significant rates of attrition of individual ChipSats throughout a mission.

The CubeSat element of the system is a standards based ChipSat deployment mechanism designed to drop into unmodified commercial off the shelf CubeSat structures from multiple manufacturers. The deployer can range in size from 0.2 to 3U and can be entirely independent of the host CubeSat or CubeSat compatible piggyback or smart ballast rideshare. Typically, however, a mission specific 1-6U CubeSat will be launched to transport ChipSats to a deployment point using an on-board propulsion system capable of imparting 1km/s+ delta-V such as a water fuelled EPiC system, or a Xenon fuelled ion drive. Post deployment, the CubeSat supports the ChipSats by providing services such as data relay.

The ChipCube project is an open source open access project using elements designed for KickSat and from the Open Source Space System. A single quantum of exploration (such as an individual ChipSat) will be inexpensive enough that all its costs (including manufacture, deployment and operation) could be afforded by a private individual for education, entertainment or profit. Prototypes to demonstrate all elements of the system have been built

or are under construction, and a launch opportunity is being sought for an end to end demonstration mission.

## **Session B.2 – Science: Technologies and Missions to Enhance Interplanetary CubeSat Science**

### **B.2.1 Interplanetary Radio Occultation CubeSat Constellation**

Kerri Cahoy (MIT), Ingrid Beerer (MIT), Anne Marinan (MIT), Sami Asmar (NASA JPL), Paul Withers (Boston University), and Luke Moore (Boston University)

A constellation of CubeSats can use small and simple spacecraft radio transmitters and receivers to globally and frequently measure temperature, pressure, and electron density profiles of a planet’s atmosphere and ionosphere with a technique called radio occultation. During a radio occultation experiment, a stable radio signal is transmitted to or from a spacecraft as it drops behind the limb of a planet. The electromagnetic signal interacts with the molecules in the planet’s atmosphere and the charged particles in its ionosphere. The vertical distribution of the molecules and charged particles creates a refractivity gradient. In geometrical optics terms, the electromagnetic ray travels straight through “empty” space but is symmetrically “bent” as it encounters the refractivity gradients of the atmosphere and ionosphere. The received frequency of the signal is thus slightly but detectably shifted from the initial frequency. These measured frequency residuals or amount of “bending” can be inverted to calculate atmospheric neutral densities or ionospheric electron densities of the volume of atmosphere through which the ray passed, from which high vertical resolution profiles can be derived.

The Interplanetary Radio Occultation CubeSat Constellation (IROCC) concept consists of six 3U CubeSats, each contained by a Poly-Picosatellite Orbital Deployer (P-POD) as a secondary payload on a larger interplanetary spacecraft. We discuss system design trades and requirements for this constellation, from deployment of the CubeSats after orbit insertion around a planet or satellite to orbital decay of the constellation. Trades analyzed include the timing of P-POD deployments into the desired orbit planes that also minimize any risk to a primary mission, the radio occultation experiment configuration itself (multiple frequencies, intersatellite links, signal to noise ratios, timing, and tracking), the different architectures for transmission of the collected radio occultation data back to Earth, the opportunity to study atmospheric drag as the CubeSat orbits decay, and planetary protection requirements on CubeSats. Additional target-specific parameters are also considered, such as the reduced amount of available solar power for the already-tiny CubeSats at larger distances from the Sun,



the radiation environment, the presence or absence of a magnetic field, orbital decay and mission duration, and the selection of radio occultation frequencies to correspond to the spectral features and compositions of the targets.

## B.2.2 Enhancing Radio Science Missions with CubeSats

Kamal Oudrhiri (NASA/JPL), Sami Asmar (NASA/JPL),  
and Kerri Cahoy (MIT)

Radio science conventionally studies the planets and their atmospheres as well as the solar wind via their effects on the amplitude and phase of radio signals between a spacecraft and a Deep Space Network station. The measurements are conventionally made at the earth station. For some observations, scientific return can be improved if the measurements were made at the spacecraft.

These measurements are accomplished by taking advantage of a high transmit power signal from a ground station with a very large antenna and the received signal with a high Signal to Noise Ratio reaching the spacecraft.

Recent advances in CubeSat technologies present a real opportunity to fly a future space qualified Radio Atmospheric Sound and Scattering Instrument (RASSI) with the capability to record key Radio Science observables and also perform any required data post-processing onboard the spacecraft.

In 2007, JPL built and successfully tested an engineering model of RASSI. For the purpose of this paper, we will assume that a flight RASSI is available to be integrated it with CubeSat bus. The interface between the two modules will be accomplished through a power switch, which will activate RASSI by CubeSat computer command, and also will enable RASSI science data and health & status telemetry to be relayed to the ground via the CubeSat telemetry transmitter.

CubeSat bus is also assumed (at a minimum) to provide structure, computing, thermal management, ranging, attitude determination and communications: transmit telemetry and receive commands in S-Band and have the capability to coherently translate the uplink carrier signal and transmit it back to the ground station without any modulation. RASSI is expected to meet the allowable CubeSat mass and volume specifications and it will provide dual band capability of receiving an X-Band uplink carrier from a Deep Space Network (DSN) and S-band OR UHF signal from earth or a space asset in orbit.

In this paper we will review opportunities and benefits for using Interplanetary CubeSat in conjunction with RASSI to improve Radio Science accuracy measurements in uplink (atmospheric, ring or surface) and crosslink (signals transmitted between two spacecraft) observations.

### **B.2.3 HiMARC 3D- High-speed, Multispectral, Adaptive Resolution Stereoscopic CubeSat**

Ved Chirayath and Brian Mahlstedt (Stanford University)

We present a novel, low cost solution that addresses the fundamental aperture limitation of all CubeSat based imagers to date while providing rapid, multispectral, high-resolution stereographic imaging of terrestrial and astronomical targets using an unconnected array of four 3U synthetic aperture optical telescopes. Further, using proprietary dithering algorithms, drizzle methods, lucky imaging and a new method of spatial oversampling we contend with the atmospheric seeing problem of terrestrial targets and the optical diffraction limit of aperture limited systems. We present unprecedented high resolution images of the lunar surface as imaged from an 8" Earth based amateur telescope using these techniques as proof of concept with resolutions capable of resolving features left by Apollo missions. This corresponds to a resolution limit of at least 5cm looking at Earth from LEO. Each 3U CubeSat is designed with a 670mm baseline synthetic aperture f/2 Ritchey-Chrétien optical system with zero deployables beyond a single hinge solar array. Through ground testing, we demonstrate new technologies that allow for further optical performance beyond the diffraction limit, potentially redefining modern optical telescope theory and obviating the need for future large aperture telescope missions. Together, our constellation has the equivalent light gathering capability of a traditional 16" RC telescope while maintaining a 3U form factor and a fractionated design. Each satellite telescope is coupled to a monochrome CCD sensor, optimized for a particular optical bandwidth from IR (2000 nm) to optical to UV (200 nm) so the constellation can simultaneously image a target in multiple wavelengths, providing a multispectral image three to four times faster than filter wheel systems. Lastly, we demonstrate the stereographic imaging capability of an independent four-satellite telescope design from ground testing using an array of amateur telescopes to stereograph lunar surface features.

## **B.2.4 Nanosatellite for Earth Environmental Monitoring: The MicroMAS Project**

William Blackwell (MIT Lincoln Laboratory), Kerri Cahoy (MIT Space Systems Laboratory), David Miller (MIT Space Systems Laboratory), Idahosa Osaretin (MIT Lincoln Laboratory), and Annie Marinan (MIT Space Systems Laboratory)

The Micro-sized Microwave Atmospheric Satellite (MicroMAS) is a 3U CubeSat (34.05 x 10x10 cm, ~4kg, ~12W average power, ~15kbps average data rate) hosting a passive microwave spectrometer with nine channels operating near the 118.75-GHz oxygen absorption line. The focus of the first MicroMAS mission (hereafter, MicroMAS-1) is to observe convective thunderstorms, tropical cyclones, and hurricanes from a near-equatorial orbit. A MicroMAS-1 flight unit is currently being developed for a 2014 launch to be provided by the NASA CubeSat Launch Initiative program. A parabolic reflector is mechanically rotated approximately once per second as the spacecraft orbits the earth, thus directing a cross-track scanned beam with FWHM beamwidth of 2.4 degrees, yielding an approximately 20-km diameter footprint at nadir incidence from a nominal altitude of 500 km. Radiometric calibration is carried out using observations of cold space, the earth's limb, and an internal noise diode that is weakly coupled through the RF front-end electronics. A key technology feature is the development of an ultracompact intermediate frequency processor module for channelization, detection, and A-to-D conversion. The antenna system and RF front-end electronics are highly integrated, miniaturized, and optimized for low-power operation. In this talk, the MicroMAS-1 mission concept of operations will be discussed including the science program, the radiometer payload will be described, and the spacecraft subsystems (avionics, power, communications, attitude determination and control, and mechanical structures and mechanisms) will be summarized. Test data from the recently completed MicroMAS Engineering Development Model (EDM) will also be presented.

## **B.2.5 The Phoenix Program: CubeSats as an Option for Repurposing Geostationary Assets**

Jaime Ramirez-Riberos (Aurora Flight Sciences Corporation)

DARPA's Tactical Technology Office has proposed a mission to repurpose apertures from defunct Geostationary assets, and CubeSats can play an important role in achieving the objective. The PHOENIX program's goal is to develop a set of tools to detach and reuse the apertures from old communication satellites. Such tools include enhancement to a servicer spacecraft with robotic arms that will perform the detachment tasks but also the development of sets of small 'Satlets', or constituent pieces that are to be attached to the aperture to perform the required tasks.

In our approach risk and costs can be minimized by careful utilization of COTS components, and CubeSats provide a standard platform that might facilitate the design. The Phoenix mission Satlets can base their architecture on CubeSat COTS components, from the bus structure to electronic components and solar panels, however, the operation environment beyond LEO is a complete new regime. The design of the satlets has very much in common with interplanetary CubeSats, can provide lessons to the Interplanetary CubeSat community and can learn much from it, from the different communication schemes to the approaches to radiation hardening.

Our talk will provide a perspective into the design of the Phoenix program Satlets based on CubeSat architectures, the advantages, disadvantages and expected results.

## Session C.1 – Technology: Propulsion Issues for Interplanetary CubeSat Missions

### C.1.1 Ion Drive Interplanetary CubeSat

Carl Brandon (Vermont Technical College)

A triple unit ion drive CubeSat spacecraft suitable for Lunar or interplanetary travel is being developed at Vermont Technical College with The University of Vermont and Norwich University, through a NASA Consortium Development Grant. The structural elements will be of carbon fiber composite. There will be a 1 kg scientific instrument payload. It is based on the Lunar SMART-1 spacecraft of the European Space Agency (ESA). Our design will use the CubeSat-sized NASA-JPL developed miniature xenon ion thruster MiXI with a thrust of 1.5 mN and a specific impulse of 2,500 - 3,200 seconds. With this thruster, a 0.75 kg propellant load of 300 atmosphere xenon would give a  $\Delta v$  of about 3,500 - 4,500 m/s. 50W of power for the thruster will come from photovoltaic cells on the spacecraft and four fold out double length panels. The control software for the mission is being written in Ada / SPARK which has a record of producing very reliable software, with about 1% the error rate of C.

A low energy trajectory provides a transfer to the Moon from a geostationary transfer ellipse through a Lissajous orbit at the Earth-Moon L1 Lagrange point. This strategy takes advantage of the complex dynamical behavior of the trajectory near the L1 point, and from a Lissajous orbit about L1 it is possible to access various lunar and planetary orbital planes with different inclinations and ascending nodes using a minimal  $\Delta v$ . The second type of indirect trajectory is of the type used by the ESA SMART-1 mission in 2003. The spacecraft is first put into a geostationary transfer ellipse. It then elongates its Earth elliptical orbit and utilizes lunar resonance maneuvers to minimize propellant use. A final continuous thrust maneuver can be used to perform a lunar orbit capture at a distance of about 60,000 km from the lunar surface or to initiate a Hohmann transfer to Mars. For these transfers, there will be great demands on spacecraft navigation.

Navigation is by a NovAtel OEMV-1 GPS, with CoCom limits removed, and a star tracker camera. We will use the NASA Goddard developed GPS Enhanced Onboard Navigation System (GEONS) software rewritten in Ada / SPARK. GEONS will analyze both the GPS signal and the celestial information from the star tracker camera. We have been selected for a NASA launched ELaNa IV mission for a single CubeSat which will test this navigation system in orbit in 2013.

## C.1.2 Ion Electropray Thruster Assembly for CubeSats

François Martel (Espace Inc.) and Paulo Lozano (MIT)

The miniature ion electropray thrusters developed at MIT can be operated as very high resolution actuators for precision thrusting of space structures. Their small size and high Isp make them also ideal for CubeSat propulsion and attitude control. We present and describe a sixteen thruster assembly currently under development that provides several hundred meters of Delta V to CubeSats with pitch, roll and yaw control, fitting in a volume of 1/3 of a CubeSat. The assembly provides very high resolution voltage (16 bits) and pulse control and is applicable to interplanetary propulsion and precision pointing of CubeSats. With a few hundred grams of additional propellant such assembly could also bring a LEO 3U CubeSat to escape velocity. One application of interest among many is for the control of a swarm of nanosats deployed into a large baseline sparse array antenna for RF imaging from interplanetary space.

### C.1.3 ESTCube-1: Stepping Stone for Fast Interplanetary Travel

Mart Noorma, Umas Kvell, Andris Slavinskis, (University of Tartu / Tartu Observatory), Jouni Envall and Pekka Janhunen  
(Finnish Meteorological Institute)

ESTCube-1 is the first satellite that will measure the electric solar wind effect. It is a single unit CubeSat which will be launch-ready by late-2012.

The electric solar wind sail (E-sail) technology relies on long, thin, conductive, centrifugally deployed tethers for extracting thrust from the solar wind dynamic pressure. A 100 kg E-sail module would have a hundred 20 km long tethers that will be charged to 20...40 kV positive potential. This creates a rather large electric field which in interaction with the solar wind at 1 AU distance from the Sun produces 1 N of thrust.

Designing the E-sail experiment for a single unit CubeSat on low Earth orbit (LEO) has the advantage of a low cost in orbit test, but also faces numerous challenges. For maximum benefit to the full-size E-sail development, the ESTCube-1 experiment will deploy a single 10 m long tether in LEO using centrifugal force – the same manner as the full-size E-sail would be.

Limited by the space of the single unit CubeSat standard, only magnetic torquers will be used for attitude control, including single axis spin-up to 1 rev/s for the centrifugal tether deployment. The successful deployment is verified by measuring the change in the spin period – as the tether is unreeled with a controllable motor, the spin rates slows down. A miniaturized on-board imaging system is used for additional verification – this requires the tether end-mass to have a white matte coating.

The tether that will be used is a 4-fold Heytether structure made from 25...50  $\mu\text{m}$  thick aluminum wires. The tether lifetime in LEO will be shorter than in interplanetary space, as in addition to the micrometeoroids, there are numerous space debris particle populations.

When applying a positive potential to the tether, using a cold-cathode electron gun, the interaction between the charged tether and the ionospheric plasma can be observed. By turning the electron gun on and off in sync with the spin half-periods, the resulting change in the spin rate can be measured and the magnitude of E-sail force assessed.

Accurate measurement can only be done in specific regions of the satellite's high-inclination orbit as to compromise between minimizing the Lorentz force from the tether's interaction with the Earth's magnetic field, having accurate enough ionospheric plasma measurement data available and assuring ground contact during the experiment.



### C.1.4 E-Sail Test Mission: Reaching the Solar Wind With a CubeSat

Jouni Envall, Petri Toivanen, Pekka Janhunen  
(Finnish Meteorological Institute, Finland)

The electric solar wind sail, or E-sail, is a novel propellantless propulsion method, invented at the Finnish Meteorological Institute in 2006 [1,2]. It harnesses the momentum of solar wind plasma to produce thrust for a spacecraft. The sail consists of long, centrifugally stretched conducting tethers, kept at high positive voltage with respect to the solar wind plasma. The estimated effectiveness in terms of produced impulse per unit mass is 100 to 1000 times higher than that of ion engines and chemical rockets, respectively. Once operational, the E-sail could revolutionize the space travel within the solar system and its surroundings.

E-sail is currently being developed to TRL 4-5 under the European Union funded project ESAIL. Two CubeSat missions are being prepared, both of which will test certain E-sailing concepts at LEO. The Estonian ESTCube-1 is to be launched during the first half of 2013 and the Finnish Aalto-1 in 2014.

The next logical step in space testing would be to take the satellite into solar wind. In our paper we discuss ideas of how to achieve this goal with a 3U CubeSat. Our platform would include four tethers, each 200-400 m long. The satellite would be placed in an Earth orbit with an apogee high enough to reach the solar wind. Once in orbit, the tethers shall be deployed from their storage reels by spinning the satellite and using centrifugal force to stretch the tethers. When voltage is applied to the tethers, the resulting E-sail force can be observed as a change in the orbital parameters.

Comparing such mission to the conventional CubeSat missions at LEO, the most demanding challenges arise from the relatively high delta-v requirement of both reaching a proper orbit and producing the required spin to open the tethers, together with issues related to communications and radiation tolerance.

In our paper we introduce a concept of utilizing a piggyback launch to GTO and elevating the orbit apogee to 160000 km with an on-board thruster. If an electrolysis propulsion system, such as suggested by Zeledon and Peck [3], was utilized, we estimate that 1 kg of water as propellant would enable both the orbit elevation and the satellite spin-up.

[1] Janhunen and Sandroos, *Ann. Geophys.* 25 (2007) 755.

[2] Janhunen et al., *Rev. Sci. Instrum.* 81 (2010) 111301.

[3] Zeledon and Peck, "Electrolysis Propulsion for CubeSat-Scale Spacecraft,"  
AIAA SPACE 2011 Conference & Exposition, Long Beach, CA, Sep 27-29, 2011.

## **Session C.2 – Technology: Propulsion Issues and Launching Capabilities for Interplanetary CubeSat Missions**

### **C.2.1 ULA Rideshare with CubeSat Missions for Lunar and Planetary Exploration**

Jake Szatkowski (United Launch Alliance)

United Launch Alliance (ULA) launch vehicles have a long history of providing high-value payload accommodations for a variety of customer spacecraft and missions, including planetary missions to Mercury, Venus, Mars, Jupiter, Saturn, Pluto, and Asteroids.

Rideshare - the approach of sharing available performance margin with a primary spacecraft - provides satellite developers the opportunity to get their spacecraft to orbit and beyond in an inexpensive and reliable manner. The ULA Atlas V and the Delta IV LVs have Rideshare capabilities that support a wide range of spacecraft sizes, from the smallest CubeSats, to the largest dual-manifest payloads. I will brief an overview of the rideshare capabilities that are available with current status.

This presentation will focus on CubeSat - Rideshare delivery options for the Moon, Mars, and NEO's. Reference missions using the Adapter Deck (A-Deck) system and a new 3rd-stage solution called the Multi-payload Utility Lite Electric (MULE) Stage will be discussed.

## C.2.2 nanoTHOR and PowerCube: Affordable Launch and Propulsion for Deep-Space CubeSats

Robert Hoyt and Jonathan Wrobel (Tethers Unlimited, Inc.)

The development of CubeSats and other nanosatellite platforms has enabled many space missions to be conducted at a significantly lower cost and on a shorter timeline than traditional spacecraft platforms. Ongoing development of CubeSat buses with high-power and processing capabilities, high-bandwidth communications, and maneuvering propulsion could enable them to play a significant supporting role in NASA's efforts to explore Near-Earth Objects (NEOs), Mars, and the Moon. Currently, however, there exists no clear path for frequent, affordable launch of CubeSats into interplanetary trajectories. Opportunities for secondary ride-share launches into deep space are exceedingly rare, and limitations upon stored chemical energy imposed by primary payload safety considerations make integration of high-thrust rockets highly problematic. We will present preliminary development of two innovative technologies that may together provide an affordable path to interplanetary launch of CubeSats while meeting primary payload safety requirements. The first is the "Nanosatellite Tethered High-Orbit Release" (nanoTHOR) module, which will use a lightweight, high-strength momentum-exchange tether to scavenge the orbital energy and residual propellant of GEO rocket stages to enable multiple CubeSats carried as secondary payloads to be injected into Earth-escape trajectories. The second is the PowerCube™ system, which integrates a high-power deployable solar array, an electrolysis fuel-cell, a simple pressure-fed gH<sub>2</sub>/O<sub>2</sub> pulsed thruster, and a 'carpal-wrist' gimbal mechanism to provide propulsion, power, and precision pointing for CubeSat systems. In combination, the nanoTHOR module and the PowerCube system can provide the multi-km/s delta-V's required for interplanetary missions, and do so in a very rapid manner to enable short transfer times commensurate with CubeSat lifetimes. In this presentation we will discuss concept designs, concept of operations, and anticipated performance with respect to potential missions to Near Earth Objects, the Moon, and Mars.

### C.2.3 High Delta-V Propulsion for CubeSats

Vlad Hruby, Tom Roy, Nathaniel Demmons, Kurt Hohman,  
and Mike Tsay (Busek Co. Inc.)

Busek Co. Inc. has developed four types of electric propulsion thruster systems for high Delta-V CubeSat missions. These include the electrospray thruster, micro-resistojet and RF ion thruster. Each will be described in the paper along with achievable mission parameters and niche applications.

For 25 years, Busek Co. Inc. has been working with government, academia and industry to develop electric propulsion (EP) for spacecraft, recently culminating in several flight demonstration missions on small satellites. The appeal of EP is that it offers exceptional propellant efficiency (compared to traditional chemical propulsion), which in turn gives spacecraft the capability of performing large delta-V maneuvers at the cost of relatively little propellant. Though developed for small satellites, Busek has been actively miniaturizing its EP systems to mass, volume and power consumption that is relevant to CubeSat applications. This work has resulted in the development of four EP technologies, each of which allows CubeSats to achieve a performance niche previously attainable only in their larger counterparts. Applications range from precision attitude control (10uN-s impulse bits) to large delta-V maneuvers (up to 410m/s in less than 1U volume). Each of the four EP systems - electrospray thruster, micro-resistojet and RF ion thruster - are under 1U volume and include propellant storage and management, as well as power electronics and digital interface to the host CubeSat.

The electrospray thruster is a 1U module ideally suited to provide moderate thrust/high-delta-V primary propulsion to a CubeSat. The 9W unit is capable of delivering 1050N-s impulse and 410m/s delta-V to a 3kg CubeSat. The technology is derived from the only space qualified electrospray propulsion system delivered to JPL for the NASA-ESA LISA Pathfinder mission.

The ammonia micro-resistojet module delivers higher primary (5mN) and warm-gas attitude control propulsion, ideally suited for high thrust / proximity operations. The 10W unit is capable of delivering 300 N-s impulse at 87 m/s total delta-V. The miniature valves are derived from flight valves developed for the LISA Pathfinder mission.

The RF Ion Thruster is a 1U module that is best suited to provide lower thrust and high delta-V primary propulsion to a CubeSat. The 10W unit is capable of delivering 868 N-s and 300m/s delta-V to a 3kg CubeSat. The RF Ion thruster uses miniature valves and propellant-less cathode neutralizer

derived from flight units developed for the LISA Pathfinder mission. The unit features a novel high efficiency self-resonating RF power supply.



## **Session C.3 – Technology: Navigation, Control, Tracking, and Formation for Interplanetary CubeSat Missions**

### **C.3.1 A Novel Hemispherical Anti-Twist Tracking System for CubeSat Applications (CubeHATTS)**

Eli Bashevkin, Andrew Kalman, Joe Kenahan, Brian Manning, and Brian Mahlstedt (Stanford University)

Satellites must often point a device continuously at an object as the satellite and/or object move through space. On an interplanetary mission, a movable antenna reduces the radio requirements to communicate across large distances to Earth and an articulated propulsion module enables increased spacecraft control with fewer thrusters. Continuously tracking the sun with the onboard solar array will maximize power generated. With these devices, connections are typically made between the articulated device and a fixed base, around which the devices rotates in one or more axes while tracking. Implementing these connections can be a challenge in size-constrained applications or when uninterrupted tracking is required. Within the small satellite realm, some new solutions (e.g., using a Canfield joint) have recently been developed to address this problem. Given the mass and volume constraints imposed upon CubeSats, the authors feel that none of the existing solutions solve the problem elegantly or efficiently. A new, simple two degree of-freedom (2-DOF) joint – the Hemispherical Anti-Twist Tracking System (HATTS) – is proposed that allows tracking through a sphere with continuous rotation while avoiding any twist in the connection(s) from the device to the base. This design is notable for its ability to continuously rotate and for its simplicity; the HATTS joint has a reduced component count and fewer interfaces between moving parts than competing solutions, thereby potentially increasing pointing accuracy while lowering cost, mass and complexity. In the CubeHATTS joint – a CubeSat-specific implementation of HATTS – two identical, symmetrically-mounted motors are rigidly affixed to the chassis of the satellite, and provide the two DOFs via dual coaxial gears operated either synchronously or differentially. CubeHATTS is able to track continuously through a hemisphere and when stowed, the entire system fits in a volume of approximately 0.25U (10cm x 10cm x 2.8cm). The authors believe that by enabling continuous pointing of a device without significantly impacting payload volume, CubeHATTS will help facilitate a new class of interplanetary CubeSat missions.

### **C.3.2 Low Mass Radio Science Transponder-Navigation Anywhere**

Courtney Duncan (NASA-JPL-Caltech)

CubeSats leaving the vicinity of earth will not have access to GPS or other forms of terrestrial navigation. The Low Mass Radio Science Transponder (LMRST) is a bare-bones, two-way Doppler and ranging transponder, based on well established navigation techniques in use by the Deep Space Network. LMRST-Sat is a TRL-raising demonstration mission for a developmental model of the X-Band LMRST exciter. Ka-Band and higher power versions are also in development.

In addition to navigation throughout the solar system, LMRST enables radiometric science such as gravity field determination and planetary atmosphere profiling via radio occultation.

This presentation will describe LMRST, LMRST-Sat, and possible future uses of the technology.



### C.3.3 The MotherCube Distributed Architecture for CubeSat Cluster Missions

Justin McClellan, Jaime Ramirez, and Maxim Chtangeev  
(Aurora Flight Sciences)

The CubeSat standard has enabled low-cost science missions in near-Earth orbit and potentially beyond. Designing a mission within the constraints of the CubeSat size, weight, and power (SWaP) limitations is a challenge. Aurora has developed the MotherCube distributed architecture to enable clusters of CubeSats to perform the tasks of larger, more costly monolithic satellite. Enabling cluster missions are centimeter-precision differential GPS measurements, a CubeSat-scale 100  $\mu\text{N}$  efficient propulsion system, and computationally efficient trajectory planning and cluster control algorithms capable of running on the PIC 24 processor.

Cluster control algorithms are under development to achieve the requirements of the mission while meeting the specific design constraints of a CubeSat. Some challenges that must be addressed include (1) the difficulties that arise from the scenario where thrust can only be provided in one direction along the body frame (common in larger satellites as well), and (2) limitations due to attitude control being performed using authority-limited magnetic torque coils. Simulation is showing positive control of attitude and cluster geometry with propellant usage minimized at separation distances of 10 km.

The MotherCube satellite itself is biased toward performing the functions of a central node in a cluster including downlink, processing, and storage. Shifting these functions to the MotherCube frees up SWaP on the “DaughterCubes” for payload sensors. Continued work on a scalable, high-thrust CubeSat propulsion system will allow distributed clusters to leave Earth orbit perform interplanetary missions.

### **C.3.4 The Location-Scheduled Control Architecture as Applied to Interplanetary CubeSats**

Matthew Sorgenfrei and Sanjay Joshi  
(University of California, Davis)

The use of CubeSat-scale spacecraft for scientific exploration beyond low Earth Orbit will result in as-yet unexplored system requirements for the attitude determination and control subsystem (ADCS). Past missions have demonstrated the efficacy of CubeSats for both technology demonstrations and scientific exploration, but this foundational work has largely relied on the low Earth orbit (LEO) environment to succeed. In particular, the standard suite of attitude determination sensors and control actuators are largely inapplicable to the exploration of a near Earth object or another planet, requiring a fundamental redesign of the spacecraft ADCS. In this work we apply a recently reported control system design architecture known as location-scheduled control to the emerging challenge of designing the ADCS of a CubeSat for interplanetary exploration. The concept of location-scheduled control (LSC) makes use of the basic modularity of CubeSats, as motivated by the CubeSat Standard, to optimize both the physical location of the spacecraft ADCS and the parameters of the control law being implemented.

Under LSC, the spacecraft designer is able to select a system configuration that is optimized for the particular science payload being flown, an important feature for interplanetary operations. When operating beyond LEO a CubeSat will no longer be able to rely solely on compact sensor systems such as magnetometers and sun sensors, and will also require additional radiation hardening for the majority of its components. As such, the overall volumetric constraints on the system will be much tighter while the performance requirements of the ADCS will likely be higher than a traditional CubeSat mission. To solve this problem, LSC makes use of a genetic algorithm to search the space of candidate system designs, considering both physical configuration and controller parameters. The final output is a location-based schedule of gains for a certain set of rotational maneuvers which can be referenced by the system designers. In this work, we demonstrate the use of location-scheduled control for the problem of optimizing the system configuration of a six cube (6U) CubeSat tasked with performing a large-angle reorientation in a deep space environment.

### C.3.5 Attitude Control System for Arc-Second Stabilization of 30Kg Micro Astronomy Satellite

Takaya Inamori (The University of Tokyo), Nobutada Sako (Sinsyu University), and Shinichi Nakasuka (The University of Tokyo)

These days, small satellites provide space access to broader range of satellite developers and attract interests because of shorter development period at smaller cost. These small satellites are applied to several sophisticated missions such as astronomical observation and remote sensing. An example of these satellites is a micro astronomy satellite, Nano-JAMSINE (Nano-Japan Astrometry Satellite Mission for INfrared Exploration), which has been developed at the University of Tokyo. The objective of the mission is to obtain three-dimensional position of stars. In order to obtain the scientific data, the satellite attitude should be stabilized to an accuracy of 1 arc-second, which is generally achieved with a conventional large satellite. The objective of the research is to propose methods to achieve the precise attitude control for small satellite sophisticated missions.

It is usually difficult to achieve precise attitude control in small satellites because of the following two reasons. Firstly, the effects of attitude disturbances are stronger because of smaller moment of inertia in a small satellite. Specifically, a magnetic torque is the dominant disturbance in a small satellite missions, even though the magnetic torque is small disturbance in a large satellite. Secondly, there are strict power, space, and weight constraints in small satellite missions. Therefore, precise ADCS devices are not available for a small satellite such as a ring laser gyroscope for the precise attitude rate estimation and a tip tilt mirror for the reduction of the RW disturbance effect.

This research proposes novel methods to solve these problems to achieve the precise attitude control in small satellites. For the first problem, the research proposes an in-orbit magnetic compensation method to reduce the effect of the magnetic disturbance using MTQs. For the second problem, the research proposes novel methods to use conventional devices effectively. For the precise attitude rate estimation, the research proposes a rate estimation method using star blurred images obtained by attitude sensors. For the reduction of the RW disturbance, the research proposes a novel attitude control strategy in which only smaller RWs are needed. Several these proposing methods are verified using an in-orbit remote sensing satellite PRISM. From simulation results and in-orbit performance, the research concludes that the methods are useful and effective to achieve the precise attitude control systems. The realization of a low-cost satellite with the

precise control system in a short development period will clear the way for new space system applications for the future.

## Session P.1 – Poster Session

### **P.1.1 Real-Time Attitude-Independent Three-Axis Magnetometer and Gyro-Bias On-orbit Calibration for Pico-satellites**

Tian Xiang, Hao Wang, Ke Han, Tao Meng and Zhonghe Jin  
(Zhejiang University)

This article proposes a new real-time attitude-independent algorithm for the three-axis magnetometer (TAM) and gyro bias on-orbit calibration using only TAM measurements. As an improvement of previous researches, this method estimates the magnetometer bias vector, scale factors as well as the gyro biases all based on the unscented Kalman filter (UKF) without any attitude information. The scheme mainly consists of three steps: first, the TAM measurement model as well as the gyro model including the scale factors and biases is given. Then the attitude-independent observation model that incorporates the rate information of the gyro is derived. The model mainly relies on a conversion of the magnetometer measurement and its corresponding inertial reference vectors, together with their derivatives. Finally, the UKF is developed to implement the previous two procedures. Simulation results demonstrate that the proposed method is feasible for the calibration of both TAMs and gyros. The convergence time of the gyro bias estimates  $\beta$  is less than 100s, and the  $3\sigma$  bounds of them after convergence are  $0.004^\circ/\text{s}$ ,  $0.004^\circ/\text{s}$  and  $0.008^\circ/\text{s}$  respectively for each axis. Meanwhile, the magnetometer parameters converge near their true value within 1000s, and the  $3\sigma$  bounds of the biases  $b$  are 0.01mG, 0.04 mG and 0.008 mG respectively for each axis, while those of the scale factors are  $4.02 \times 10^{-5}$ ,  $2.69 \times 10^{-4}$ ,  $2.57 \times 10^{-5}$ ,  $1.12 \times 10^{-4}$ ,  $3.0 \times 10^{-5}$  and  $7.54 \times 10^{-5}$  respectively for each element of the D matrix. Moreover, the proposed method is tested using the on-orbit data from the ZDPS-1A pico-satellites that have been on orbit since September 22th, 2010. Results again validate its applicability. Taken together, the simulation and on-orbit data results indicate that the performance of the calibration algorithm can meet the requirements of on-orbit missions of pico-satellites. Therefore, it is ready to be applied to such missions of subsequent pico-satellite models.

## **P.1.2 UPESSAT: Seismic Activity Determination Nanosatellite**

Samaksh Behl, Aakanksha Dhar, and Yachna Gola  
(University of Petroleum and Energy Studies, India)

CubeSats are becoming crucial in the present day scenario of space research as they not only serve to be a low cost research tool for testing and validation of the next generation micro sized payloads but they also play a vital role in space exploration. With the first CubeSat mission, accomplished by Russia in June 2003, various Universities have been coming up with the idea of Student Satellite Projects. A method of indicating India's investment in developing a space industry is research projects within Universities. This gave birth to the idea of UPESSAT. UPESSAT's primary scientific mission is to detect magnetic fluctuations using magnetometer at certain timelines and certain locations, record these fluctuations and downlink the magnetic signal data. The magnetic fluctuation data will be superimposed with the seismic data for that particular location and timeline, which may lead to pioneering techniques to predict earthquake activity. This paper describes the design of the primary satellite structure and the analysis used to arrive at the design. The internal and external configurations of the spacecraft along with the estimated mass properties of the integrated satellite will be described. Finite element method will be used to simulate the environment that the structure will undergo. It will be used to predict behaviour of the complex geometry to be used as the satellite's structure. The main frame of the satellite is composed of beams and thin plates which will be checked for structural integrity. Correlating these analyses with several static and modal tests, the model boundary conditions will be verified. Set to launch in 2014, and bound for a 705 km inclined polar orbit, UPESSAT is a prime example of CubeSat technology.

### **P.1.3      A CubeSat-based Science Mission for Meteor Research**

Ryo Ishimaru, Masanori Kobayashi, Takafumi Matsui  
(Institute of Technology, Japan),  
Shinsuke Abe (National Central University (IANCU), Taiwan),  
and Yukihiro Takahashi (Hokkaido University)

Particles and fragments from asteroids and comets can be observed during their entry into the Earth's atmosphere as meteors; accordingly, the meteors give us the information in primordial materials, such as their size, orbit, composition and, possibly, origin. Although meteors have been observed mainly from the ground so far, ground-based observations have a limitation in the observation conditions, such as the observational range and time. The ground-based observations cannot cover the entire globe because it is difficult to set observation stations on the ocean. On the other hand, weather conditions (e.g., cloudy) prevent the ground observers from observing meteors continuously. To overcome these limitations, we are planning to build and launch a new CubeSat to observe meteors from space. A space-based observation by an earth-orbiting satellite enables a continuous global observation of meteors. Our satellite is a three-unit (3U) CubeSat carrying some optical instruments, such as camera and photomultiplier.

## **P.1.4 Nano-habitats: Advanced CubeSats to improve Design and Construction of HSF Hardware**

Raul Polit-Casillas (NASA JPL)

In the beginning of the Italian Renaissance, Master Architect Bramante showed with the Tempietto of San Pietro in Montorio (Rome) that small works could very well lead and influence how much bigger projects could be done, frequently this is the only way. This paper is focused in the development and advance CubeSats to serve a dual purpose that eventually will lead to a more affordable human exploration of space. On one side, it presents how the small scale of these spacecraft could become a most efficient test bed for new types of advance designs and automated construction processes in order to develop the next generation not only of space habitats but also big-scale space hardware, like telescopes or solar arrays. For this, not only the physical implementation of the vessel but also the whole design and manufacturing process could be redefined using state-of-the-art tools and techniques. As a result this paper develops how a CubeSat, while attending current functions and requirements of today's mission, could be redesigned following the same principles that more complex hardware would require. A CubeSat, turned into a nano-habitat architecture would allow to test either specific parts or whole new constructive designs. This paper will present how this is a new area of research and interdisciplinary collaboration that later on can be translated to many more space projects and procedures. On the other side, the concept of the nano-habitat also explores structural and space constructions matters, materials and implementations as well as systems integration to think in the use of these spacecraft size for space life sciences purposes taking into account the design challenges of that approach. Analyzing requirements and constrains of current design and manufacturing techniques, virtual model capabilities and current state-of-the-art CubeSat development this paper present some conclusions and leading research lines related to the author's research work that are currently under development. The use of this small scale, and the affordability to explore and research advance concepts that could later on be translated into more complex developments represents a likely milestone for one of our biggest problems for space exploration besides its educational interests for collaboration among agencies, universities and industry from different sector. Nano-habitats design and test can contribute to a more affordable, sustainable, adaptable and efficient hardware in and for space, in perhaps our biggest challenges in the coming years.



**P.1.5      A New Sensor Platform for the  
Interplanetary CubeSat Missions**

Sanjay Srikanth Nekkanti (Lulea University of Technology),  
Vinay Ravindra (University of Wurzburg),  
and Loganathan Muthuswamy (ISRO - Retired Scientist)

This paper would discuss the development of a new open source sensor platform for the interplanetary CubeSat missions. All the existing earth orbiting CubeSat missions employ a beacon to transmit the housekeeping parameters of the satellite, the limitation being they can transmit only on VHF/UHF or S band. The new sensor platform developed will be capable of detecting the level of radiation observed at any particular time and will have the capability to transmit this information along with the housekeeping parameters of the satellite using a software defined radio. This system would thus help us in identifying places like the South Atlantic anomaly region, which might exist in different locations in our solar system. This paper would thus discuss the feasibility and engineering aspects involved in the development of such a platform for the interplanetary CubeSat missions.

## P.1.6 Active Pointing, on a Budget

Aaron Goldstein and Chris Kady (Sun Devil Satellite Laboratory)

Interplanetary travel, much like early earth exploration, is an advent that produces not only tremendous public interest but ground breaking technology as well. The capability of active pointing on a CubeSat is an essential part of an interplanetary mission. Using simulation methods, to implement a control scheme, we present a 3u CubeSat with the capabilities of pointing to within  $\pm 0.1$  degrees bore-sight, with body rate control by implementing momentum wheel and magnetorquer actuation. The active sensory and actuator system is expected to cost around \$100,000, which is considerably lower than previous works. Through the development of an accurate and inexpensive active pointing system, interplanetary CubeSat travel is made more accessible.

## 9. Social Program

### **MIT and Space Systems Lab (SSL) Tour (29<sup>th</sup> May)**

Campus and Space Systems Lab tours will leave from the main lecture hall at 6:15pm on Tuesday, May 29<sup>th</sup>. The tours will be led by MIT students Mary Knapp and Rebecca Jensen-Clem and will end at the dinner reception in the exhibition hall (E14 MPR-674) at 7:15pm.

### **Dinner Reception (29<sup>th</sup> May)**

Dinner will be provided for all conference attendees at 7:20pm on Tuesday May 29<sup>th</sup> in the exhibition hall (E14 MPR-674). All iCubeSat participants are encouraged to attend!

### **Dinner in Boston (30<sup>th</sup> May)**

Attendees who have signed up in advance for the optional dinner in Boston will meet at the Cambridge Brewing Company at 8:00. This dinner is not included in the cost of registration.

### **Tips for a weekend in Boston:**

*Historic Sites:* The Freedom Trail ([www.thefreedomtrail.org](http://www.thefreedomtrail.org)) is a 2.5 mile walking tour of 16 historic sites in Boston. The trail can be self-guided or part of an organized tour. Trail highlights include the Boston Common, Old North Church, Paul Revere's house, Bunker Hill, and the USS *Constitution*.

*Museums:* Boston is also home to several world-renowned museums, including the Museum of Fine Arts, Isabella Stewart Gardner Museum, Boston Museum of Science, and the MIT Museum.

*Dining:* Boston's North End neighborhood, or "Little Italy," provides many excellent Italian restaurants at a range of prices.

*Family-Friendly:* The Boston Common is the oldest public park in the country, and includes large open areas, a frog pond, and the famous swan boat rides.

**Please find a map of Boston in your iCubeSat Workshop bag!**

## 10. Acknowledgements

<b>Sponsors</b>	
<b>MIT Department of Earth, Atmospheric, and Planetary Science</b>	<b>MIT Department of Aeronautics and Astronautics</b>
Aeronautical and General Instruments Limited (AGI)	Busek Co. Inc.
Comtech AeroAstro	Draper Laboratory
JA	Journal of Small Satellites (JoSS) Online
Micro Aerospace Solutions	Sinclair Interplanetary
Stanford University Space Systems Development Laboratory (SSDL)	United Launch Alliance (ULA)

<b>Volunteers</b>		
<b>First Name</b>	<b>Last Name</b>	<b>Affiliation</b>
Jameson	Nash	MIT
Alibay	Farah	MIT
Sung Won	Lim	GenSpace
Rebecca	Masterson	MIT
Koki	Ho	MIT
Tom	Coles	MIT
Vlada	Stamenkovic	MIT
Mark	Chodas	MIT
Kevin	Stout	MIT
Evan	Wise	MIT

The organizing committee would also like to thank the staff of the MIT Media Lab, the Department of Earth, Atmospheric, and Planetary Science (EAPS), and the Department of Aeronautics and Astronautics for their time and support.

We are grateful to Professor Sara Seager for her contributions to the audiovisual system and for her advice throughout the organizational process.

We would also like to thank Gwen Gettliffe (MIT) for creating the opening iCubeSat video and Dr. Alvar Saenz Otero for his help in organizing the SSL tour.

# **11. iCubeSat 2013**

## **Cornell University, Ithaca, NY, USA**

### **28-29 May 2013**

#### **Call for abstracts**

iCubeSat, the Interplanetary CubeSat Workshop, will address the technical challenges, opportunities, and practicalities of space exploration with CubeSats. The workshop will provide a unique environment for open practical collaboration between academic researchers, industry professionals, policy makers, and students developing this new and rapidly growing field.

#### **Technical Program**

Talks and round tables will focus on three themes: technology, science, and open collaboration.

The program will also include unconference sessions to provide additional opportunities to engage with the interplanetary CubeSat community and potential collaborators. Talks and supporting material will be streamed and posted on the conference website. A lively social program in and around summertime Ithaca will be arranged for participants and their guests.

#### **Exhibition**

CubeSat specialists and other vendors are invited to contact [exhibit@iCubeSat.org](mailto:exhibit@iCubeSat.org) for details.

#### **Dates and deadlines**

<b>May 29<sup>th</sup> 2012</b>	iCubeSat 2013 registration opens at <a href="http://iCubeSat.org">iCubeSat.org</a>
<b>April 1<sup>st</sup> 2013</b>	Abstract upload deadline
<b>April 15<sup>th</sup> 2013</b>	Notification of abstract acceptance
<b>May 24<sup>th</sup> 2013</b>	Presentation (and optional paper) upload deadline

#### **Location**

The second Interplanetary CubeSat conference will be held at Cornell University, Ithaca, New York, USA on Tuesday, May 28<sup>th</sup> through Wednesday, May 29<sup>th</sup>, 2013.



