2016
Interplanetary Small Satellite Conference

beyond LEO

Conference Program

Small satellite developments in:

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

Hosted by:

California Institute of Technology
Pasadena, CA
April 25-26, 2016

www.intersmallsatconference.org

Monday, April 25, 2016

Time	**Event**
8:00-9:00	Registration
9:00-9:50	**Keynote Speaker: Larry James**
9:50-10:05	Coffee Break
10:05-11:35	**Session A: Mission Concepts** *Session chairs: A. Babuscia and C. Norton*
	A.1 Lunar Flashlight: Illuminating the Lunar South Pole (*P. Hayne*)
	A.2 BioSentinel: Mission Development Update of a Radiation Biosensor to Gauge DNA Damage and Repair on a 6U Nanosatellite (*R. Hanel*)
	A.3 The Lunar Polar Hydrogen Mapper (LunaH-Map) Mission (*C. Hardgrove*)
	A.4 LunarIceCube: Lunar Volatile Dynamics from a First Generation Deep Space CubeSat (*P. Clark*)
	A.5 KitCube: Lunar CubeSat Mission Demonstrating Laser Communications and Green Monopropellant Technology (*K. Cahoy*)
	A.6 Small Lander and CubeSats on ESA's Asteroid Impact Mission – a GNC Perspective (*M. Casasco*)
11:35-12:05	**Session A Q&A Panel**
12:05-13:10	Lunch
13:10-14:25	**Session B: Telecommunication** *Session chairs: K. Cheung and C. Lee*
	B.1 Iris: SmallSat Transponder for Exploaration on Mission One (And Others) (*C. Duncan*)
	B.2 Ka-Band Mesh Reflector Deployable Antenna for Earth Science and Deep Space Telecommunication (*N. Chachat*)
	B.3 A Scalable Deployable High Gain Antenna-DaHGR (*K. Kelly*)
	B.4 Inflatable Antenna for CubeSat: X-Band Design (*A. Babuscia*)
	B.5 Optical Communications for Deep Space CubeSat (*W. Farr*)
14:25-14:50	**Session B Q&A Panel**
14:50-15:10	Coffee Break

Monday, April 25, 2016 *(continued)*

Time	Event
15:10-16:25	**Session C: Propulsion and Launch Systems** *Session chairs: D. Dalle and J. Thanga*
	C.1 iEPSat: CubeSat Propelled to Lunar Space by Ionic Liquid Electrospray Thrusters (*D. Krejci*)
	C.2 An Enabling Low-Power Magnetically Shielded Hall Thruster for Interplanetary SmallSat Missions (*R. Conversano*)
	C.3 Role of Small Satellites in Fast Mars Transit (*D. Taylor*)
	C.4 Interorbital Systems: Launch Vehicle Services to LEO, Luna, and Beyond (*R. Milliron*)
	C.5 An Orbital Maneuvering Vehicle for Transport Beyond Earth Orbit (*C. Loghry*)
16:25-16:50	**Session C Q&A Panel**
16:50-17:35	**Session D: Ground Support** *Session chairs: A. Babuscia and A. Chandra*
	D.1 What the Deep Space Network (DSN) Can Do for You (*S. Waldherr*)
	D.2 Working Toward More Affordable Deep Space CubeSat Communications: MSPA and OMSPA (*D. Abraham*)
	D.3 Adapting a Sophisticated Ground Data System for Use by a Deep Space Cubesat Mission (*P. Di Pasquale*)
17:35-17:50	**Session D Q&A Panel**
18:00-20:00	Dinner and Social

Tuesday, April 26, 2016

Time	Event
8:00-9:00	Registration
9:00-9:50	**Keynote Speaker: Mark Robinson**
9:50-10:05	Coffee Break

Tuesday, April 26, 2016 *(continued)*

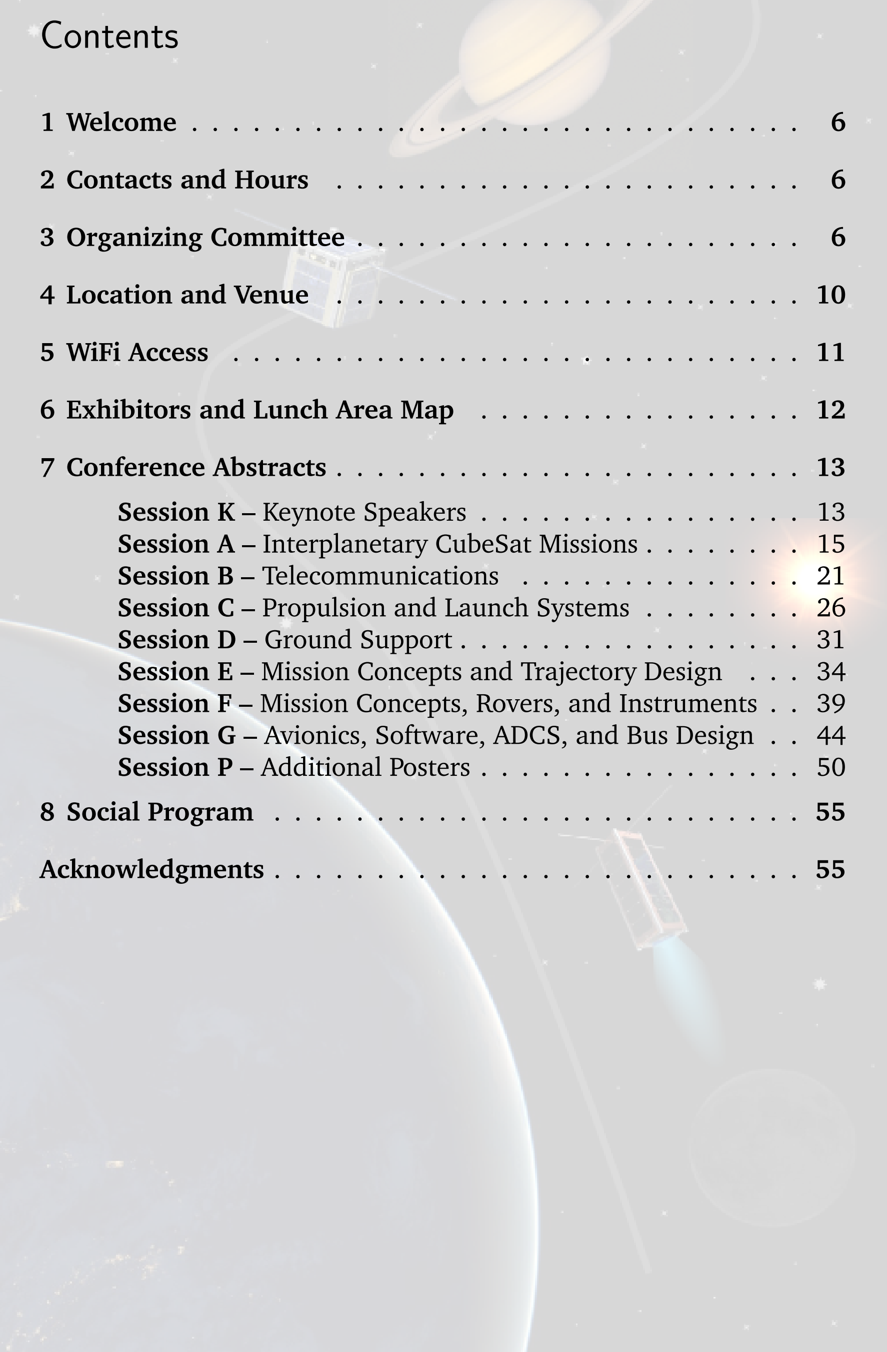
Time	Event
10:05-11:20	**Session E: Mission Concepts and Trajectory Design** *Session chairs: K. Cahoy and F. Alibay*
	E.1 Europa Surface and Plume 3D eXploror (ESP-3DX): A CubeSat Mission Concept to Search for Plumes on Europa (*J. Thanga*)
	E.2 CubeSat for Asteroid Exploration (*G. Landis*)
	E.3 Constellations of CubeSats (*J. Lazio*)
	E.4 Mars Telecommunications CubeSat Constellation Relay (*D. Spencer*)
	E.5 Evaluation of Stable Periodic Orbits about Non-Spherical Objects (*J. Swenson*)
11:20-11:50	**Session E Q&A Panel**
11:50-13:00	Lunch
13:00-14:15	**Session F: Mission Concepts, Rovers, and Instruments** *Session chairs: T. Imken and P. Clark*
	F.1 Spacecraft/Rover Hyprids for the Exploration of Small Solar System Bodies (*B. Hockman*)
	F.2 Using Statistical Risk Assessment to Optimize the Design of Inflatable Membrane Structures in Low Earth Orbit (*E. Asphaug*)
	F.3 Small Gravity Geophysics Inside CubeSat Centrifuge (*S. Hosseini*)
	F.4 ASU Interplanetary CubeSat (*G. Dektor*)
	F.5 Sampling Venus' Atmosphere with a Low-Cost, Free-Flying Smallsat Probe (*A. Freeman*)
14:15-14:40	**Session F Q&A Panel**

Tuesday, April 28, 2014 *(continued)*

Time	**Event**
14:40-15:00	Coffee Break
15:00-16:30	**Session G: Avionics, Software, ADCS, and Bus Design** *Session chairs: L. Jones and Y. He*
	G.1 Reference CubeSat Core Avionics for Deep Space Science (*J. Castillo-Rogez*)
	G.2 Rad Hard and CryoElectronics for CubeSats in Jovian Radiation Environments (*R. Frampton*)
	G.3 Reliable Software for an Interplanetary CubeSat (*G. Brandon*)
	G.4 Characterization of the BCT Nano Star Tracker Performance (*K. Lo*)
	G.5 Market Evolution and Commercialization of Nano, Micro, MiniSats (*M. Villa*)
	G.6 Moving Toward a More Capable Small Satellite Bus for Interplanetary Missions (*G. Lightesy*)
16:30-17:00	**Session G Q&A Panel**
17:00-17:05	Closing Remarks

Poster Session

Session P.1
P.1 The JPL CubeSat Development Laboratory (*P. Clark*)
P.2 Inflatable Antennas for CubeSats and Small Spacecraft: Advances in Shape Retention and Stowage (*A. Chandra*)
P.3 Asteroid Origins Satellite I: An Orbit Planetary Science Laboratory (*A. Thoesen*)
P.4 Risk Assessment: Freeman Dyson's Noah's Ark Egg Strategy (*J. Vos Post*)
P.5 Next Generation of Telecom Web Services for CubeSat Scheduling (*M. Johnston*)



Contents

1 **Welcome** 6

2 **Contacts and Hours** 6

3 **Organizing Committee** 6

4 **Location and Venue** 10

5 **WiFi Access** 11

6 **Exhibitors and Lunch Area Map** 12

7 **Conference Abstracts** 13

- **Session K** – Keynote Speakers 13
- **Session A** – Interplanetary CubeSat Missions 15
- **Session B** – Telecommunications 21
- **Session C** – Propulsion and Launch Systems 26
- **Session D** – Ground Support 31
- **Session E** – Mission Concepts and Trajectory Design . . . 34
- **Session F** – Mission Concepts, Rovers, and Instruments . . 39
- **Session G** – Avionics, Software, ADCS, and Bus Design . . 44
- **Session P** – Additional Posters 50

8 **Social Program** 55

Acknowledgments 55

1. Welcome

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

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

Thank you for joining us in Pasadena.

—*The Organizing Committee*

2. Contacts and Hours

The registration desk will be open from 8:00 am on April 25 and from 8:00 am to 3:00 pm on April 26. Please don’t hesitate to contact the organizing committee at info@intersmallsatconference.org at any time during the conference.

3. Organizing Committee

Alessandra Babuscia received her B.S. and M.S degrees from the Politecnico di Milano and her Ph.D. degree from the Massachusetts Institute of Technology in 2012. She is currently Telecommunication Engineer in the Communication Architecture Research Group, NASA Jet Propulsion Laboratory. She is PI for the Inflatable Antenna for CubeSat project, task manager and telecom engineer for LunaH-Map mission, telecom engineer for VERITAS step 2 proposal, telecom engineer for ASTERIA mission, telecom engineer for RainCube mission, telecom chair lead for JPL TeamXc, and involved in many CubeSat mission design concepts and proposals. Her current research interests include communication architecture design, statistical risk estimation, expert elicitation, inflatable antennas, and communication system design for small satellites and CubeSats. Dr. Babuscia received the Amelia Earhart Fellowship in 2010 and 2011, became a Gordon Engineering Leadership Fellow in 2010 and 2011, and received the Teaching Assistant Award from the MIT Aeronautics and Astronautics Department in 2010, and the Top Graduate Award in the B.S. Program in 2005 and in the M.S. Program in 2007 from the Politecnico di Milano.

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

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

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

Carlyn Lee is a software engineer for the Telecommunication Architecture Group at NASA Jet Propulsion Laboratory. She is involved in link budget analysis tools development and optimization for space communication and navigation. Her research interests include communication systems, networking architecture, and high-performance computations. She received her B.S. and M.S. degrees in computer science from the California State University, Fullerton in 2011 and 2012.

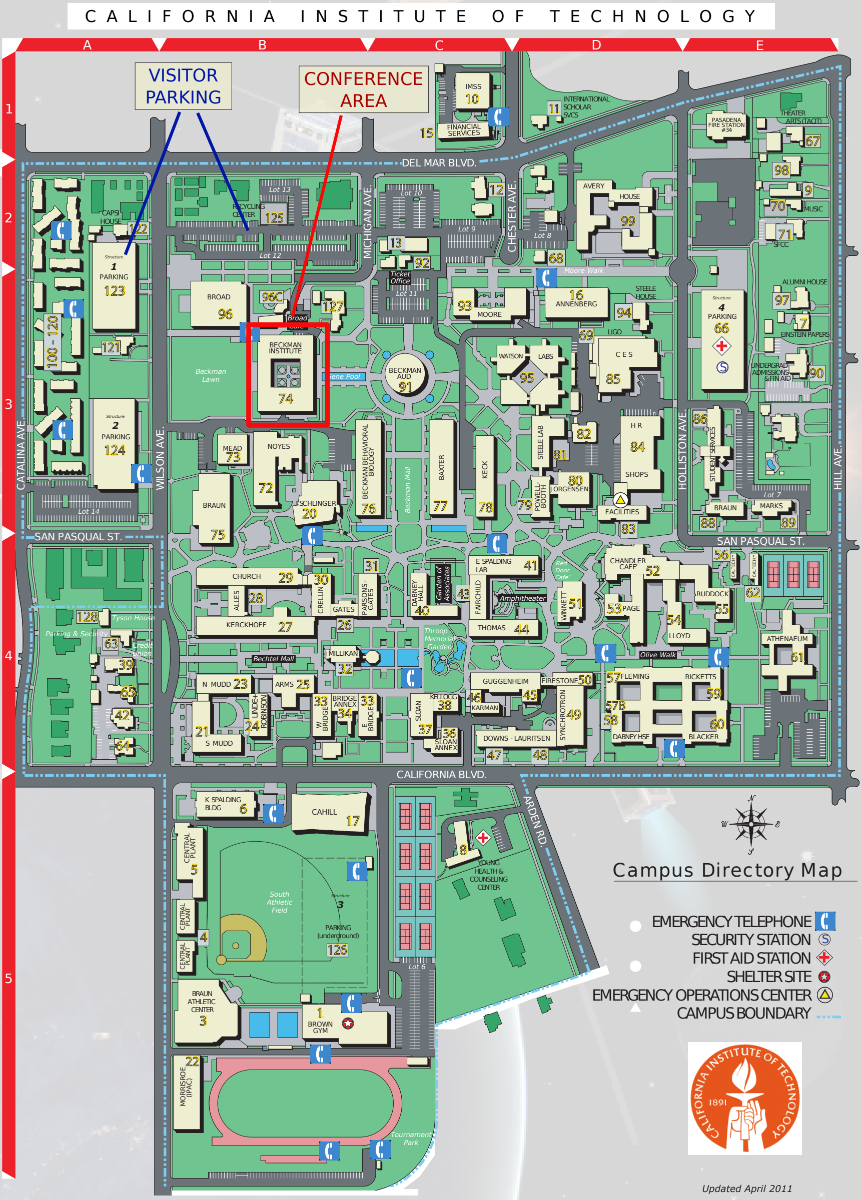
Derek Dalle is an aerodynamics engineer in NASA Ames' Computational Aerosciences branch (Code TNA) with Science & Technology Corp. His current focus is aerodynamics for the Space Launch System using NASA's High-End Computing Capability efficiently. He received a Ph.D. from Michigan in 2013. His interests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

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

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

4. Location and Venue

The conference will take place at 400 S. Wilson Ave, Pasadena, CA.



CALIFORNIA INSTITUTE OF TECHNOLOGY

Buildings by Name	Bldg No	Map Grid
1320 E San Pasqual (Caltech Y)	56	E4
1350 E San Pasqual (Caltech Y Annex)	62	E4
263 S Chester (International Scholar Services)	11	D1
275 S Hill (Theater Arts (TACIT))	67	E1
287 S Hill (Rickenbaugh House)	98	E1
293 S. Chester (Child Care Center)	12	C2-D2
295 S Hill	9	E2
305 S Hill (Music House)	70	E2
315 S Hill (SFCC)	71	E2
315 S Wilson (CAPSI-Educational Outreach)	122	A2
320 S Michigan (Campus Programs Annex)	13	C2
330 S Chester (Campus Programs Office)	68	D2
330 S Michigan Ave (Audio Visual Annex)	13A	C2
332 S Michigan (Campus Ticket Office)	92	C2
345 S Hill (Alumni House)	97	E2
345 S Michigan (Tolman-Bacher House)	127	B3
355 S Holliston (Steele House)	94	D3
363 S Hill (Einstein Papers House)	7	E3
375 S Wilson (Prufrock House)	121	A3
505 S Wilson (Tyson House)	128	A4
515 S Wilson (Credit Union/Parking/Security)	63	A4
525 S Wilson (U.S. Geological Survey)	39	A4
535 S Wilson (Fitzhugh House)	65	A4
551 S Wilson (Investment Office)	42	A4
565 S Wilson (Audit Svcs & Inst Compliance)	64	A4
Alles Laboratory	28	B4
Annenberg Ctr for Info Sci and Tech (IST)	16	D3
Arms Laboratory	25	B4
Athenaeum	61	E4
Avery House	99	D2
Baxter Hall	77	C3
Beckman Auditorium	91	C3
Beckman Behavioral Biology	76	B3-C3
Beckman Institute	74	B3
Blacker House	60	E4
Braun Athletic Center	3	B5
Braun House	88	E3
Braun Laboratories	75	B3
Bridge Annex	34	B4
Bridge Laboratory - East	33E	B4
Bridge Laboratory - West	33W	B4
Broad Café	96C	B3
Broad Center for the Biological Sciences	96	B3
Brown Gymnasium	1	B5
Cahill Ctr for Astroscience and Astrophysics	17	B5
Catalina Graduate Housing	100-120	A2-A3
Central Engineering Services (CES)	85	D3
Central Plant	5	B5
Chandler Dining Hall (Chandler Café)	52	D4
Chem Storage (Solvent Storage)	30A	B4
Church Laboratory	29	B4
Cogeneration and Cooling Towers	4	B5
Crellin Laboratory	30	B4
Dabney Hall	40	D4
Dabney House	58	D4
Downs Laboratory	47	C4
Facilities/Facilities Management	83	D3
Financial Services	15	C1
Firestone Laboratory	50	D4
Fleming House	57	D4
Gates Annex	26	B4
Guggenheim Laboratory	45	C4
Human Resources/Facilities Management Shops	84	D3
Information Management Systems & Svcs (IMSS)	10	C1
Jorgensen Laboratory	80	D3
Karman Laboratory	46	C4
Keck Laboratories	78	C3
Kellogg Radiation Laboratory	38	C4
Kerckhoff Annex	27A	B4
Kerckhoff Laboratories	27	B4
Lauritsen Laboratory	48	D4
LIGO	69	D3
Linde+Robinson Laboratory	24	B4
Lloyd House	54	D4-E4
Marks House	89	E3
Mead Laboratory	73	B3
Millikan Library	32	B4
Moore Laboratory	93	C3
Morrisroe Astroscience Laboratory (IPAC)	22	B5
Mudd Laboratories - North	23	B4
Mudd Laboratories - South	21	B4
Noyes Laboratory	72	B3
Page House	53	D4
Parking Structure 1 (South Wilson)	124	A3
Parking Structure 2 (Wilson Avenue)	123	A3
Parking Structure 3 (California Avenue)	126	B5
Parking Structure 4 (Holliston Avenue)	66	E3
Parsons-Gates Hall of Administration	31	B4
Powell-Booth Laboratory	79	D3
Recycling Center	125	B2
Ricketts House	59	E4
Ruddock House	55	E4
Satellite Utility Plant	66B	E3
Schlinger Lab for Chemistry and Chem Engr	20	B3
Sherman Fairchild Library	43	C4
Sloan Annex	36	C4
Sloan Laboratory	37	C4
South Undergrad Housing Complex Basement	57B	D4
Spalding, Eudora (Eudora Spalding Laboratory)	41	C4
Spalding, Keith (Keith Spalding Building)	6	B5
Steele Laboratory	81	D3
Student Activities Center	57B	D4
Student Services, Center for	86	E3
Synchrotron Laboratory	49	D4
Thomas Laboratory	44	C4
Transportation & Grounds Operations	82	D3
Undergraduate Admissions & Financial Aid	90	E3
Watson Laboratories	95	C3-D3
Winnett Center	51	D4
Young Health and Counseling Center	8	C5

Functions & Places	Bldg No or Map Grid
24-Hour Security	66
Administration	31
Admissions Office, Graduate	86
Admissions Office, Undergraduate	90
Alumni House	97
Amphitheater	C-4
Athletics (Indoors)	2-3
Athletics (Outdoors-South Athletic Fields)	B5-C5
Auditorium (Annenberg Auditorium)	16
Auditorium (Baxter Lecture Hall)	77
Auditorium (Beckman Auditorium)	91
Auditorium (Beckman Institute Auditorium)	74
Auditorium (Hameetman Auditorium)	17
Auditorium (Lees-Kubota Lecture Hall)	45
Auditorium (Norman Davidson Lecture Hall)	27
Auditorium (Ramo Auditorium)	77
Auditorium (Rock Auditorium)	96
Auditorium (Sharp Lecture Hall)	25
Auditorium (Sturdivant Lecture Hall)	72
Bechtel Mall	B4
Beckman Lawn	B3
Beckman Mall	C3
Bookstore	51
Caltech Credit Union (CEFCU)	63
Campus & Community Relations	32
Campus Programs Office	92
CAPSI (Caltech Precollege Science Initiative)	98
Card Services	51
Career Development Center	86
Corporate Relations	32
Development & Institute Relations	32
Diversity, Center for	86
Division Office (Biology)	27
Division Office (Chemistry & Chem Engineering)	30
Division Office (Engineering & Applied Science)	44
Division Office (Geological & Planetary Sciences)	25
Division Office (Humanities & Social Sciences)	77
Division Office (Physics, Math & Astronomy)	33
Employment	84
Facilities Management	83
Faculty Club (Atheneum)	61
Faculty, Officers of the	31
Fellowships and Study Abroad	86
Financial Aid	90
Food & Dining Services (*Broad Café*)	96C
Food & Dining Services (*Chandler Café*)	52
Food & Dining Services (*Convenience Store*)	52
Food & Dining Services (*Red Door Café*)	51
Garden of Associates	C4
Gene Pool (Fountain)	B3
Governmental Relations	31
Graduate Office	86
Graphic Resources	6
Health Center	8
Human Resources	84
Humanities Reading Room	40
IMSS Help Desk	86
International Scholar Services	11
International Student Programs	86
Library (Astrophysics)	17
Library (Geology & Planetary Sciences)	23
Library (Humanities Reading Room)	40
Library (Millikan Library)	32
Library (Sherman Fairchild Library)	43
Marketing & Communications	32
Moore Walk	C2-D2
Olive Walk	D4-E4
Parking Office	63
Performing and Visual Arts	67/70
Post Office/Mail Services	6
Recreation	3
Registrar	86
Safety Office	6
Security Office	63
Staff & Faculty Consulting Center (SFCC)	71
Student Activities Center	57B
Student Services	86
Student-Faculty Programs	86
Tech Express	54
Theater Arts (TACIT)	67
Throop Memorial Gardens	C4
Ticket Office	92
Tournament Park	C5
Undergraduate Dean's Office	86
Young Health & Counseling Center	8

Bldg No	Buildings by Number	Map Grid
1	Brown Gymnasium	B5
3	Braun Athletic Center	B5
4	Cogeneration and Cooling Towers	B5
5	Central Plant	B5
6	Spalding, Keith (Keith Spalding Building)	B5
7	363 S Hill (Einstein Papers House)	E3
8	Young Health and Counseling Center	C5
9	295 S Hill	E2
10	Information Management Systems & Svcs (IMSS)	C1
11	266 S Chester (International Scholar Svcs)	D1
12	293 S Chester (Child Care Center)	C2-D2
13	320 S Michigan (Campus Programs Annex)	C2
13A	330 S Michigan (Audio Visual Annex)	C2
15	Financial Services	C1
16	Annenberg Ctr for Info Sci and Tech (IST)	D3
17	Cahill Ctr for Astroscience and Astrophysics	B5
20	Schlinger Lab for Chem and Chemical Engr	B3
21	Mudd Laboratories - South	B4
22	Morrisroe Astroscience Laboratory (IPAC)	B5
23	Mudd Laboratories - North	B4
24	Linde+Robinson Laboratory	B4
25	Arms Laboratory	B4
26	Gates Annex	B4
27	Kerckhoff Laboratories	B4
27A	Kerckhoff Annex	B4
28	Alles Laboratory	B4
29	Church Laboratory	B4
30	Crellin Laboratory	B4
30A	Chem Storage (Solvent Storage)	B4
31	Parsons-Gates Hall of Administration	B4
32	Millikan Library	B4
33E	Bridge Laboratory - East	B4
33W	Bridge Laboratory - West	B4
34	Bridge Annex	B4
36	Sloan Annex	C4
37	Sloan Laboratory	C4
38	Kellogg Radiation Laboratory	C4
39	525 S Wilson (US Geological Survey)	A4
40	Dabney Hall	D4
41	Spalding, Eudora (Eudora Spalding Laboratory)	C4
42	551 S Wilson (Investment Office)	A4
43	Sherman Fairchild Library	C4
44	Thomas Laboratory	C4
45	Guggenheim Laboratory	C4
46	Karman Laboratory	C4
47	Downs Laboratory	C4
48	Lauritsen Laboratory	D4
49	Synchrotron Laboratory	D4
50	Firestone Laboratory	D4
51	Winnett Center	D4
52	Chandler Dining Hall (Chandler Café)	D4
53	Page House	D4
54	Lloyd House	D4-E4
55	Ruddock House	E4
56	1320 E San Pasqual (Caltech Y)	E4
57	Fleming House	D4
57B	South Undergrad Housing Complex Basement	D4
57B	Student Activities Center	D4
58	Dabney House	D4
59	Ricketts House	E4
60	Blacker House	E4
61	Athenaeum	E4
62	1350 E San Pasqual (Caltech Y Annex)	E4
63	515 S Wilson (Credit Union/Parking/Security)	A4
64	565 S Wilson (Audit Svcs & Inst Compliance)	A4
65	535 S Wilson (Fitzhugh House)	A4
66	Parking Structure 4 (Holliston Avenue)	E3
66B	Satellite Utility Plant	E3
67	275 S Hill (Theater Arts (TACIT))	E1
68	330 S Chester (Campus Programs Office)	D2
69	LIGO	D3
70	305 S Hill (Music House)	E2
71	315 S Hill (SFCC)	E2
72	Noyes Laboratory	B3
73	Mead Laboratory	B3
74	Beckman Institute	B3
75	Braun Laboratories	B3
76	Beckman Behavioral Biology	B3-C3
77	Baxter Hall	C3
78	Keck Laboratories	C3
79	Powell-Booth Laboratory	D3
80	Jorgensen Laboratory	D3
81	Steele Laboratory	D3
82	Transportation & Grounds Operations	D3
83	Facilities/Facilities Management	D3
84	Human Resources/Facilities Management Shops	D3
85	Central Engineering Services (CES)	D3
86	Center for Student Services	E3
88	Braun House	E3
89	Marks House	E3
90	383 S Hill (Undergrad Admis & Financial Aid)	E3
91	Beckman Auditorium	C3
92	332 S Michigan (Campus Ticket Office)	C2
93	Moore Laboratory	C3
94	355 S Holliston (Steele House)	D3
95	Watson Laboratories	C3-D3
96	Broad Center for the Biological Sciences	B3
96C	Broad Café	B3
97	345 S Hill (Alumni House)	E2
98	287 S Hill (Rickenbaugh House)	E1
99	Avery House	D2
100-120	Catalina Graduate Housing	A2-A3
121	375 S Wilson (Prufrock House)	A3
122	315 S Wilson (CAPSI-Educational Outreach)	A2
123	Parking Structure 2 (Wilson Avenue)	A3
124	Parking Structure 1 (South Wilson)	A3
125	Recycling Center	B2
126	Parking Structure 3 (California Avenue)	B5
127	345 S Michigan (Tolman-Bacher House)	B3
128	505 S. Wilson (Tyson House)	A4

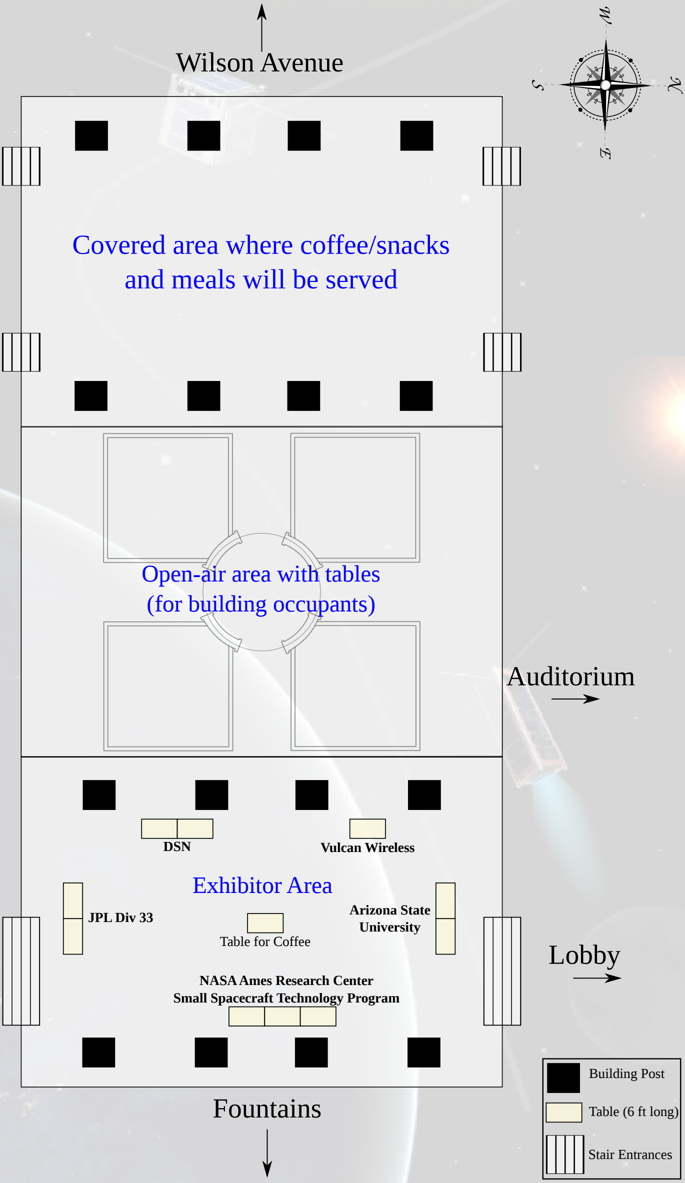
Updated April 2011

5. WiFi Access

For wireless internet access, connect to the “Caltech Guest” network.

6. Exhibitors and Lunch Area Map

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

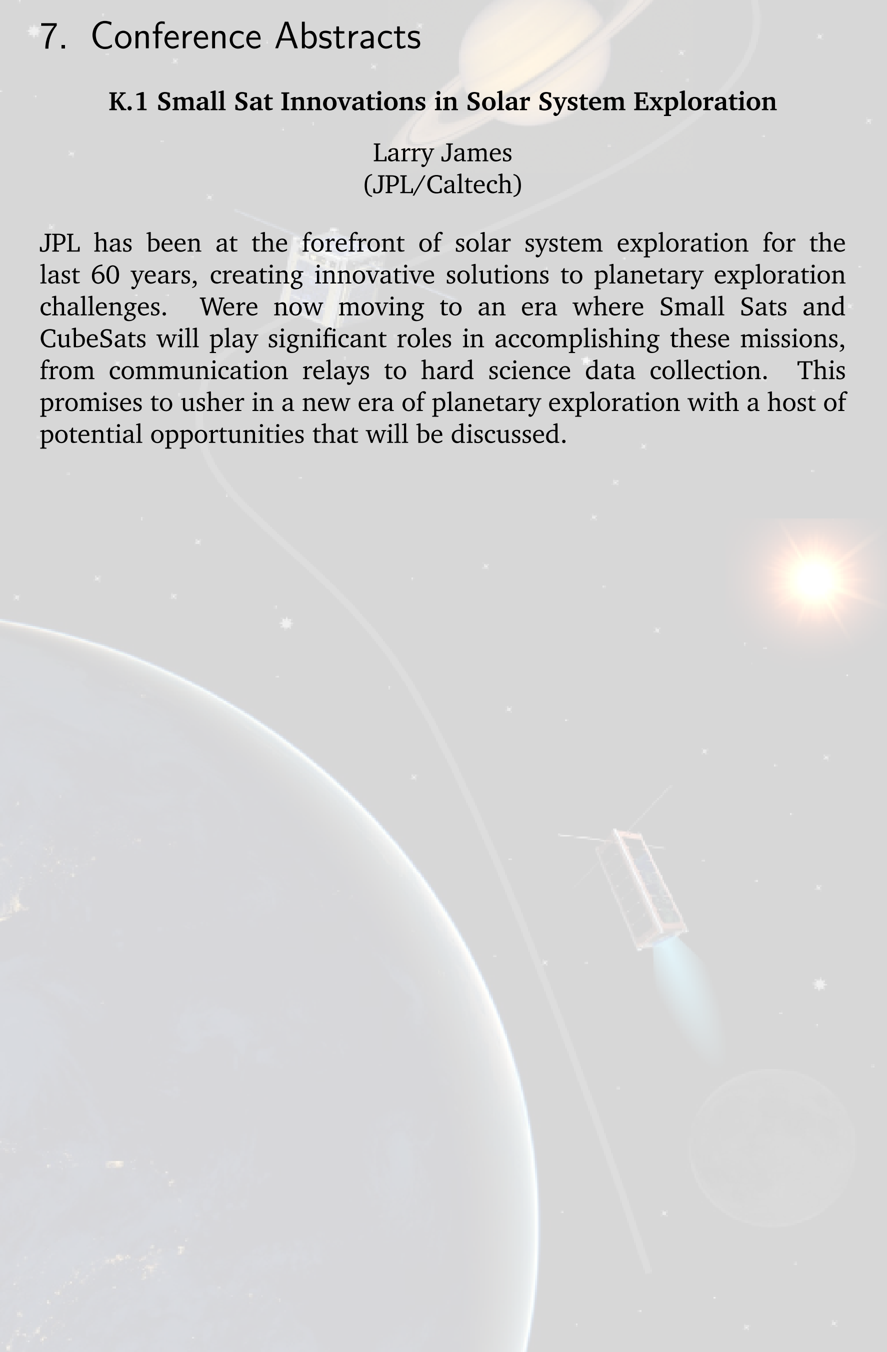


7. Conference Abstracts

K.1 Small Sat Innovations in Solar System Exploration

Larry James
(JPL/Caltech)

JPL has been at the forefront of solar system exploration for the last 60 years, creating innovative solutions to planetary exploration challenges. Were now moving to an era where Small Sats and CubeSats will play significant roles in accomplishing these missions, from communication relays to hard science data collection. This promises to usher in a new era of planetary exploration with a host of potential opportunities that will be discussed.



K.2 Swirl - Unraveling the Enigma

Mark Robinson
(Arizona State University)

Mysterious patterns of albedo contrasts, called swirls, have long captured the imagination of the scientific community. A key aspect of this interest was due to the discovery that the swirls are associated with local strong remnant magnetic fields. Thus it was natural to invoke local magnetic structures as shields that retard space weathering; regolith under the fields remains immature. Despite efforts to understand how the magnetic anomalies could result in such features, the nature of the associated magnetic anomalies and the formation mechanism of the swirls are still not known; principally because we still do not have any measurements of the swirl magnetic fields with resolution to resolve the structure of the magnetic sources.

The Swirl spacecraft meets volume and mass constraints of a standard 6U CubeSat. Arizona State University has the responsibility to design, build and carry out the mission with partnership of the Jet Propulsion Laboratory, KinetX, and Johns Hopkins University Applied Physics Laboratory.

The Swirl mission design and focused science and measurement objectives show that CubeSats can make meaningful contributions to furthering our understanding of key lunar science questions and should be part of a sustainable long term architecture to move humans out of low Earth orbit and into the Solar System through a focused path built around a series of achievable tasks within a structured time frame.

A.1 Lunar Flashligh: Illuminating the Lunar South Pole

Paul Hayne, Barbara Cohen, and Travis Imken (JPL/Caltech)

Lunar Flashlight is a low-cost cubesat mission to be launched as a secondary payload on the first test flight (EM-1) of the Space Launch System (SLS), currently scheduled for 2018. The goal of Lunar Flashlight is to determine the presence or absence of exposed water ice and map its concentration at the 1-2 kilometer scale in the permanently shadowed regions of the lunar south pole. Recent reflectance data from LRO instruments suggest water ice and other volatiles may be present on the surface in lunar permanently-shadowed regions, though the detection is not yet definitive. Understanding the composition, quantity, distribution, and form of water and other volatiles associated with lunar permanently shadowed regions (PSRs) is identified as a NASA Strategic Knowledge Gap (SKG) for Human Exploration. After being ejected in cislunar space by SLS, Lunar Flashlight will use a chemical propulstion system to maneuver into a low-energy transfer to lunar orbit and then an elliptical polar orbit, spiraling down to a perilune of 10-30 km above the south pole for data collection. Lunar Flashlight will use stacked-bar diode lasers (1.064, 1.5, 1.84, and 2.0 m) to illuminate permanently shadowed regions and measure the surface albedo in each wavelength on a single detector. Within our limited mass and power space for the instrument system, the team has been conducting analyses on design parameters to minimize the measurement uncertainty. Our spectral model uses standard optical constants for water ice and lunar regolith samples and simulants to calculate bidirectional reflectance using Hapke's formulas for a zero-phase illumination geometry. Each spectral point is ratioed to a linear interpolation or extrapolation of the two continuum channels. For a given sigma, the model is run one million times. The resulting statistics are compared to the nominal case to determine the relationship between measurement uncertainty and SNR. We have also modeled the spacecraft altitude above the lunar surface, using LOLA topography and LF trajectory files. We then use illumination models from Diviner to calculate "stray light" radiance from illuminated terrain within the instrument field of view. Finally, we have begun construction of a prototype instrument to verify the computer model of system performance. This system currently includes the InGaAs detectors, a vacuum enclosure, and a thermal control system to cool the detectors to desired temperatures. Future development of the breadboard will add lasers and lunar regolith simulant to enable end-to-end testing of the instrument system under realistic conditions.

A.2 BioSentinel: Mission Development of a Radiation Biosensor to Gauge DNA Damage and Repair Beyond Low Earth Orbit on a 6U Nanosatellite

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

BioSentinel continues the development of a 6U nanosatellite as a secondary payload launching aboard NASA's Space Launch System (SLS) Exploration Mission (EM-1), scheduled for launch in Summer 2018. For the first time in over forty years, direct experimental data from biological studies beyond low Earth orbit (LEO) will be obtained during BioSentinel's 12-month mission. BioSentinel will measure the damage and repair of DNA in a biological organism and allow us to compare that to information from onboard physical radiation sensors. In order to understand the relative contributions of the space environment's two dominant biological perturbations, reduced gravity and ionizing radiation, results from deep space will be directly compared to data obtained in LEO (on ISS) and on Earth. These data points will validate existing biological radiation damage and repair models, and for extrapolation to humans, to assist in mitigating risks during future long-term exploration missions beyond LEO.

The BioSentinel Payload will utilize the monocellular eukaryotic organism Saccharomyces cerevisiae (yeast) to report DNA double-strand-break (DSB) events that result from ambient space radiation. The S. cerevisiae strain will include engineered genetic defects to prevent growth and division until a radiation-induced DSB activates the yeast's DNA repair mechanisms. The triggered culture growth and metabolic activity directly indicate a DSB and its successful repair. BioSentinel will also include physical radiation sensors, which record the radiation environment that will be compared directly to the rate of DSB-and-repair events measured by the biosensor.

Several spacecraft bus subsystem design selections have been made and are on the path for making development units that support operation in the deep space environment, including command and data handling, communications, power generation, and attitude determination-and-control system with micropropulsion.

The Concept of Operations (ConOps) and implementation of a supporting Mission Operations System (MOS) has begun. The ConOps addresses the following areas, which pose unique challenges to a nanosatellite mission:

- Definition of mission phases, as well as definition of spacecraft operating modes and the criteria used to transition between them
- Allocation of functional responsibility between on-board functions and ground-based functions in support of operability of the spacecraft bus and payloads
- Determination of a communication pass plan and data budget that balances the need for downlinked data with strict S/C power and thermal constraints
- Derivation of radiometric tracking requirements in support of deep space navigation
- Planning for early mission activities that will occur during periods of high contention for communications assets

A.3 The Lunar Polar Hydrogen Mapper (LunaH-Map) Mission

Craig Hardgrove (Arizona State University), Igor Lazbin (Arizona Space Technologies, LLC), Hannah Kremer, (Arizona State University), and Alessandra Babuscia (JPL/Caltech)

The Lunar Polar Hydrogen Mapper (LunaH-Map) is a 6U CubeSat mission recently selected by NASA's Science Mission Directorate to fly as a secondary payload on first Exploration Mission (EM-1) of the Space Launch System (SLS). LunaH-Map is led by a small team of researchers and students at Arizona State University, in collaboration with NASA centers, JPL, universities, and commercial space businesses. The LunaH-Map mission will reveal hydrogen abundances at spatial scales below 10 km in order to understand the relationship between hydrogen and permanently shadowed regions, particularly craters, at the Moon's South Pole. The mission's primary payload is designed to use the scintillator material $\mathrm{Cs_2YLiCl_6:Ce}$, or "CLYC" to measure count rates of thermal and epithermal neutrons. Enabled by a low-thrust ion propulsion system, LunaH-Map will achieve lunar orbit insertion within $\sim$12 months of SLS separation and maneuver into a highly elliptical, low-perilune (5-10 km) orbit centered around the South Pole of the Moon. In this orbit, LunaH-Map will achieve over 140 low-altitude fly-bys of the South Pole during its two month science mission. LunaH-Map and two other secondary payloads (Lunar IceCube and Lunar Flashlight) were selected by NASA to fly on SLS EM-1 and will be the first CubeSats to explore the Moon and interplanetary space.

A.4 Lunar Ice Cube: Lunar Volatile Dynamics from a First Generation Deep Space CubeSat

Pamela Clark (JPL/Caltech), Ben Malphrus (Morehead Sate University), Robert MacDowall (NASA GSFC), David Fita (NASA GSFC), Michael Tsay (Busek)

Lunar Ice Cube, a science requirements-driven deep space exploration 6U cubesat mission was selected for a NASA HEOMD NextSTEP slot on the EM1 launch. We are developing a compact broadband IR instrument for a high priority science application: understanding volatile origin, distribution, and ongoing processes in the inner solar system. Focus on lunar exploration is especially relevant because of the Moon's accessibility as a stepping stone to the rest of the solar system, combined with its suitability as an analog with extreme range of conditions and thus an ideal technology testbed for much of the solar system. The recent announcement of opportunities to propose to fly one of cubesats to be deployed from EM1 generated a plethora of proposals for 'lunar cubes'. JPL's Lunar Flash-light, and Arizona State University's LunaH-Map, both also EM1 lunar orbiters, will provide complimentary obser-vations to be used in understanding volatile dynamics.

The Lunar Ice Cube mission science focus, led by the JPL science PI, is on enabling broadband spectral determi-nation of composition and distribution of volatiles in regoliths of the Moon and analogous bodies as a function of time of day, latitude, regolith age and composition and thus enabling understanding of current dynamics of volatile sources, sinks, and processes, with implications for evolutionary origin of volatiles. The mission is designed to ad-dress NASA HEOMD Strategic Knowledge Gaps related to lunar volatile distribution (abundance, location, and transportation physics of water ice).

Lunar Ice Cube utilizes a versatile GSFC-developed payload: BIRCHES, Broadband InfraRed Compact, High-resolution Exploration Spectrometer, a miniaturized version of OVIRS on OSIRIS-REx. BIRCHES is a compact (1.5U, 2 kg, 7W including cryocooler) point spectrometer with a compact cryocooled HgCdTe focal plane array for broadband (1 to 4 micron) measurements, achieving sufficient SNR (>400) and spectral resolution (10 nm) through the use of a Linear Variable Filter to characterize and distinguish important volatiles (water, H2S, NH3, CO2, CH4, OH, organics) and mineral bands. We are also developing compact instrument electronics which can be easily re-configured to support the instrument in 'imager' mode, once the communication downlink bandwidth becomes available, and the H1RG family of focal plane arrays. Lpsc2016

Thermal design is critical for the instrument. The compact and efficient Ricor cryocooler is designed to maintain the detector temperature below 120K. In order to maintain the optical system below 220K, a special radiator is ded-icated to optics alone, in addition to a smaller radiator to maintain a nominal environment for spacecraft electronics.

The Lunar Ice Cube team is led by Morehead State University, who will provide build, integrate and test the spacecraft, provide missions operations and ground communication. Propulsion is provided by the Busek Iodine ion propulsion (BIT-3) engine. Attitude Control will be provided by the Blue Canyon Technology XB1, which also includes a C&DH 'bus'. C&DH will also be supported, redundantly, by the Proton 200k Lite and Honeywell DM microprocessor. Onboard communication will be provided by the X-band JPL Iris Radio and dual patch antennas. Ground communication will be provided by the DSN X-band network, particularly the Morehead State University 21-meter substation. Flight Dynamics support, including trajectory design, is provided by GSFC.

Use of a micropropulsion system in a low energy trajectory will allow the spacecraft to achieve the science orbit within a year. The high inclination, equatorial periapsis orbit will allow coverage of overlapping swaths, with a 10 km along-track and cross-track footprint, once every lunar cycle at up to six different times of day (from dawn to dusk) as the mission progresses during its nominal six month science mapping period.

A.5 KitCube: Lunar CubeSat mission demonstrating laser communications and green monopropellant technology

Kerry Cahoy, Raichelle Aniceto, Kathryn Cantu, Max Yates, Angela Crews, and Maxim Khatsenko (MIT)

KitCube is a 6U CubeSat entered in the NASA CubeQuest Challenge for a launch opportunity on Exploration Mission-1 (EM-1) with the Space Launch System (SLS). KitCube is designed for the "Lunar Derby" competition, which requires the CubeSats to achieve lunar orbit. KitCube will demonstrate a relatively high delta-V green monopropellant propulsion system and a miniaturized laser communications (also called free space optical communications) payload. To achieve lunar orbit, KitCube takes a bi-elliptic trajectory to the weak stability boundary (WSB) between the Sun and the Earth at 4.5 times the Earth-Moon distance. Given the limited volume and mass available on a CubeSat, and realistic propulsion system performance, using multi-body gravitational effects is necessary to manage the excess velocity imparted by the SLS. The low-energy WSB trajectory enables KitCube to achieve lunar orbit with 150 m/sec delta-V, or an average thrust of 54 mN during a 9.7 hour finite burn. The propulsion system uses a green monopropellant, AF-M315E, developed by the Air Force Research Laboratory (AFRL), a more stable, less-toxic fuel that has a specific impulse similar to that of hydrazine. A custom propellant tank has been designed for this lunar-bound mission to maintain $\sim$500 psi as the propellant is depleted. A laser communications system is in development to achieve an expected data rate of $>$1.5 Mbps over a 30-minute interval from lunar orbit. The use of an optical communications system requires fine pointing and attitude control of the spacecraft, which is achieved by augmenting star trackers and reaction wheels and attitude sensors on the spacecraft body with a MEMS fine steering mirror. KitCube's design also combines custom with commercial off the shelf (COTS) components for the avionics and Attitude Determination and Control System (ADCS). The laser communications and green monopropellant technologies demonstrated by KitCube will lead to new scientific observation and commercial opportunities using nanosatellite platforms by enabling agile maneuvering and translation, precise pointing, and high data rate communications systems for more capable Earth orbiting spacecraft as well as for future interplanetary CubeSat missions.

A.6 Small lander and CubeSats on ESA's Asteroid Impact Mission – a GNC perspective

Massimo Casasco, Jesus Gil Fernandez, Guillermo Ortega, and
Ian Carnelli (European Space Agency)

The Asteroid Impact Mission (AIM) is a small mission of opportunity currently undergoing preliminary design (Phase B1). AIM's goals are to demonstrate a number of new technologies, to carry out fundamental asteroid research and to assess the capabilities of a kinetic impactor for planetary defence (this last goal performed in collaboration with NASA-led DART as part of the AIDA mission). Launched in October 2020, AIM will reach the binary asteroid system Didymos in 2022. The main AIM spacecraft will perform high-resolution visual, thermal and radar mapping of the Didymos system, focusing in particular on the smaller asteroid (informally called Didymoon) to build detailed maps of its surface and interior structure. The AIM main spacecraft is planned to carry three smaller spacecraft the MASCOT-2 asteroid lander, provided by DLR, as well as two CubeSats. The close proximity operations needed for deploying MASCOT-2 ad the CubeSats impose significant challenges on the GNC subsystem in terms of performance and reliability.

MASCOT-2 is a small lander (13 kg, 33x30x20 cm) that will perform in-situ investigation on the surface of Didymoon. MASCOT-2 has no means of propulsion and needs to fully rely on the AIM spacecraft for being injected into a ballistic trajectory that will allow achieving successful landing on Didymoon. The foreseen release strategy consists in injecting AIM on a safe hyperbolic arc that approaches Didymoon in the proximity of the Lagrangian point L2. MASCOT-2 will exploit the unstable manifold passing through L2 to minimise the velocity at touch-down.

Five candidate CubeSat missions are under evaluation, which involve a number of different scenarios, ranging from landing on the asteroids, to orbiting them, to monitoring the asteroids from the L4 or L5 Lagrangian points.

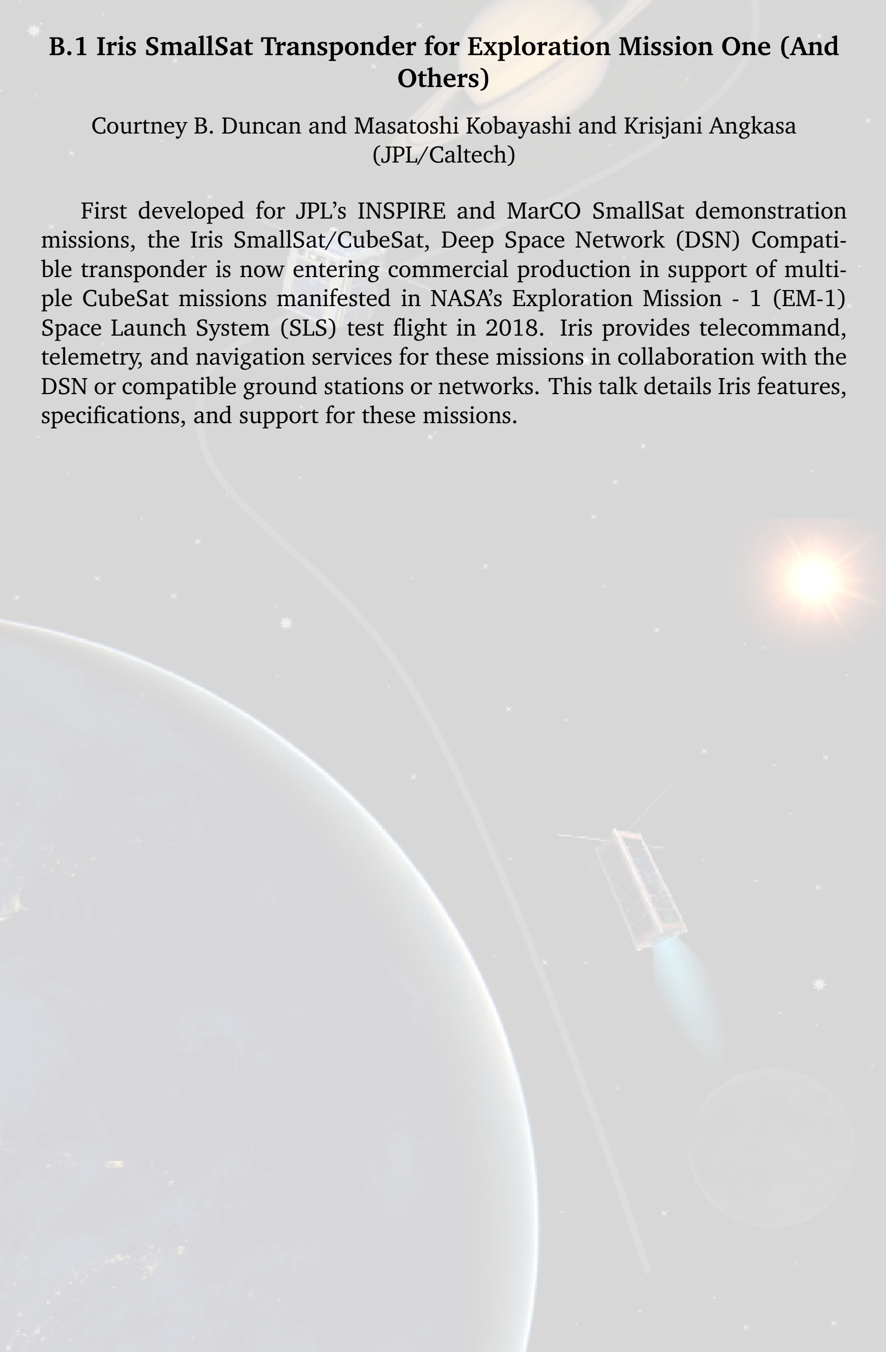
In all cases, the GNC subsystem on the AIM spacecraft is required to support the critical proximity operations in the vicinity of the asteroids by means of autonomous operations. Uncertainties in the ephemeris of the asteroids require that relative navigation techniques are used. The baseline is to use vision-based navigation techniques, exploiting the experience obtained with the Rosetta mission (with ground in the loop) and the developments for other NEO missions (e.g. Marco Polo-R). The optional use for navigation of laser and radar altimetry information as well as of infra-red images provided by payloads on board AIM is also under investigation.

The inter-satellite link that will be established between AIM and the CubeSats could also be valuable for navigating the CubeSats.

B.1 Iris SmallSat Transponder for Exploration Mission One (And Others)

Courtney B. Duncan and Masatoshi Kobayashi and Krisjani Angkasa
(JPL/Caltech)

First developed for JPL's INSPIRE and MarCO SmallSat demonstration missions, the Iris SmallSat/CubeSat, Deep Space Network (DSN) Compatible transponder is now entering commercial production in support of multiple CubeSat missions manifested in NASA's Exploration Mission - 1 (EM-1) Space Launch System (SLS) test flight in 2018. Iris provides telecommand, telemetry, and navigation services for these missions in collaboration with the DSN or compatible ground stations or networks. This talk details Iris features, specifications, and support for these missions.



B.2 Ka-band mesh reflector deployable antenna for Earth science and deep space telecommunication

Nacer Chahat
(JPL/Caltech)

Small satellite systems can uniquely enable new discoveries in space science with cost-effective solutions. Launching multiple copies of a RADAR instrument is now possible with the recent advances in miniaturized RADAR and CubeSat technologies. The Radar in a CubeSat (RainCube) mission, currently under development at NASA's Jet Propulsion Laboratory (JPL), is a 6U CubeSat precipitation RADAR.

Thanks to the simplification and miniaturization of radar subsystems, the RainCube project at JPL has developed a novel architecture that is compatible with the 6U class. In comparison to existing spaceborne radars, the RainCube architecture reduces the number of components, power consumption, and mass by several order of magnitude. This opens up a new realm of options for low-cost spacecraft platforms saving not only on the instrument implementation (especially beyond the first unit) but also on the launch and spacecraft costs. We can now consider deploying a constellation of identical copies of the same instrument in various relative positions in low Earth orbit (LEO) to address specific observational gaps left open by current missions that require high-resolution vertical profiling capabilities.

One of the major challenges faced by this mission was to develop an antenna design providing a gain of more than 42dBi, with low side lobe levels and fitting in a highly constrained volume (<1.5U). The required antenna gain and limited stowage volume dictate utilization of a deployable antenna. A deployable mesh parabolic antenna stowing in a 1.5U volume was developed at Ka-band for an Earth-Science CubeSat called Raincube (RADAR in a CubeSat). The deployable mesh antenna for RainCube was successfully designed and tested.

Another version of the antenna is currently under development for telecommunication purpose. This antenna is right handed circularly polarized (RHCP) and operates at the DNS bands (i.e. Uplink: 34.2–34.7GHz and Downlink: 31.8–32.3GHz).

B.3 A Scalable Deployable High Gain Antenna – DaHGRA Scalable Deployable High Gain Antenna

Keith Kelly and Jeff Harvey (MMA Design)

A Scalable Deployable High Gain Antenna – DaHGR MMA Design (MMA) has invented and is developing a revolutionary deployable antenna solution providing extremely high areal compaction for future microsatellite missions. Our solution combines the positive attributes of currently fielded antenna systems and will enable performance for microsatellites consistent with today's large space craft payloads. The MMA patented and patent pending Deployable High Gain Reflectarray (DaHGR) antenna has both a wideband and a narrower band configuration. The antenna architecture is realized using very lightweight flexible membrane substrates incorporating a hoop structure to deploy the membranes and maintain tension. The proposed solution builds on innovations by MMA in extremely lightweight deployable systems specific to large antennas and aerobraking systems.

Current state-of-the-art (SOA) Mesh Antennas use ribbed umbrella and hoop structures for deployment. While these are potentially scalable to some extent, they inherently have high parts count and require significant touch labor at a high number of attach points to form the desired mesh surface. These systems have constraints on their stowed volume which present challenges with small launch vehicle fairings and dispensers. The DaHGR sets a new standard for deployable antennas with 1/3 the parts count, less than 1/5 the volume (with a more favorable/flexible aspect ratio), and the cost of current SOA deployable antennas.

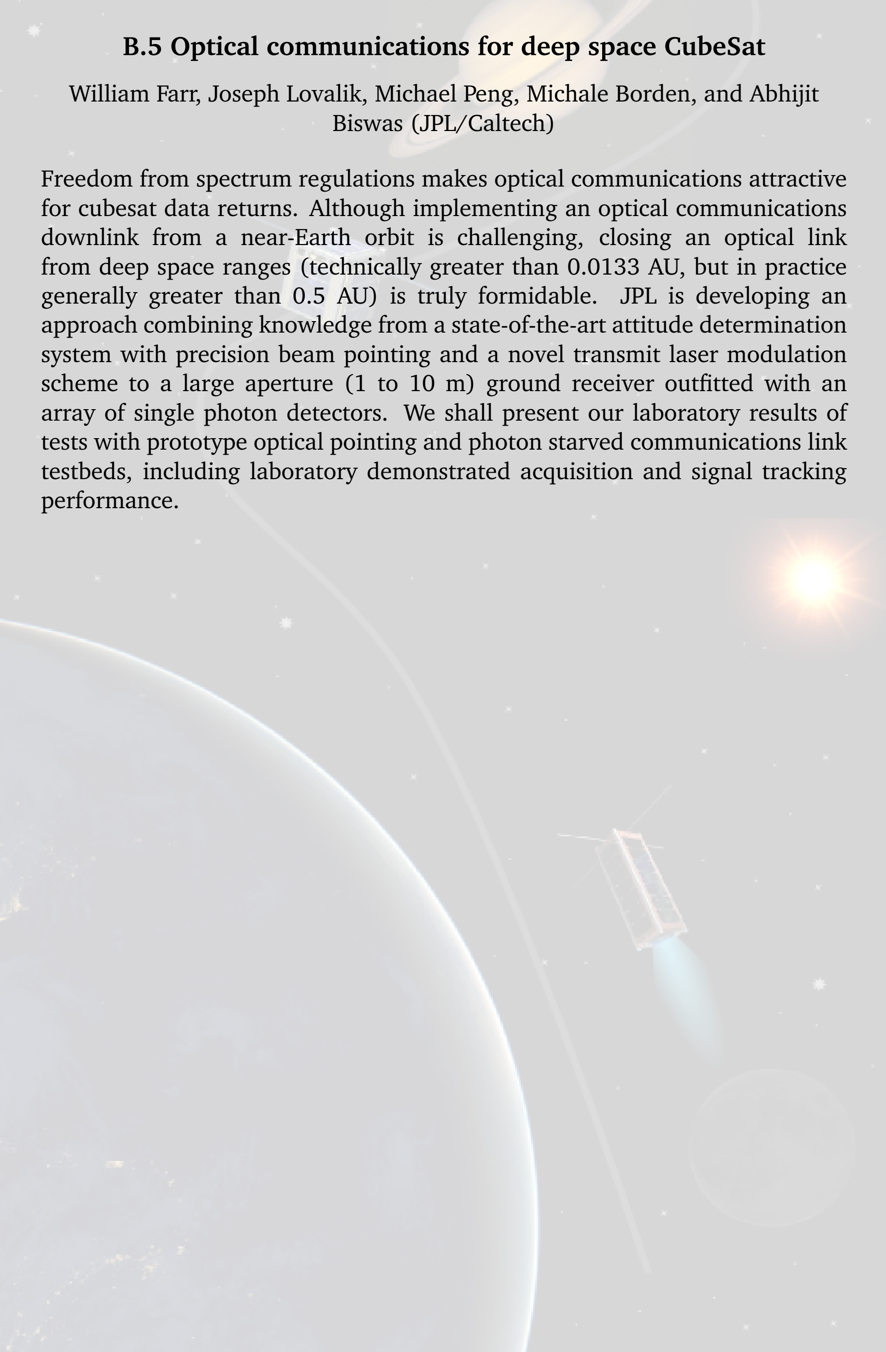
The DaHGR antenna solution combines the best attributes of successfully flown solutions. It offers advantages in performance, compaction, and simplicity and significantly reduces the development and implementation risk by leveraging proven technologies. A large space-fed reflectarray provides equivalent performance as a conventional reflector for all missions not requiring extremely large bandwidth. Bandwidths achievable by reflectarrays easily support a multitude of mission requirements.

B.4 Inflatable antenna for CubeSat: X-Band design

Alessandra Babuscia, Jonathan Sauder, Nacer Chahat, Jekan Thangavelautham, and Aman Chandra (JPL/Caltech)

Currently planned interplanetary CubeSat mission concepts have shown that one of the most challenging aspects of the design is communication. Due to the increased path distance with respect to low Earth orbit missions, interplanetary CubeSats need to be equipped with more powerful antennas to relay data from far locations in the solar system. Many research efforts are currently aiming to fill this need, as it can be seen from recent developments in reflectarray antennas and deployable antennas. The inflatable antenna is of particular interest for its stowing efficiency (20:1) and its inflation mechanism with sublimating powder. This presentation will cover the current effort of designing an inflatable antenna at X-Band. Recent results from the current design, photogrammetry tests and anechoic chamber tests will be presented. Inflation system and rigidization challenges will also be discussed.

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



B.5 Optical communications for deep space CubeSat

William Farr, Joseph Lovalik, Michael Peng, Michale Borden, and Abhijit Biswas (JPL/Caltech)

Freedom from spectrum regulations makes optical communications attractive for cubesat data returns. Although implementing an optical communications downlink from a near-Earth orbit is challenging, closing an optical link from deep space ranges (technically greater than 0.0133 AU, but in practice generally greater than 0.5 AU) is truly formidable. JPL is developing an approach combining knowledge from a state-of-the-art attitude determination system with precision beam pointing and a novel transmit laser modulation scheme to a large aperture (1 to 10 m) ground receiver outfitted with an array of single photon detectors. We shall present our laboratory results of tests with prototype optical pointing and photon starved communications link testbeds, including laboratory demonstrated acquisition and signal tracking performance.

C.1 iEPSat: CubeSat propelled to lunar space by ionic liquid electrospray thrusters

David Krejci, Fernando Mier Hicks (MIT),
Francois Martel (Espace), and Paulo Lozano (MIT)

We present a potential mission application of the ionic liquid electrospray propulsion technology developed at the Space Propulsion Laboratory of the Massachusetts Institute of Technology. Over the past year, MIT's highly miniaturized electrospray thrusters have been thoroughly characterized and matured up to a recent verification test in space. The thrusters feature porous substrates with 480 emitter tips per square centimeter, with a specific impulse >1000s and throttleable thrust of approximately 12uN per square centimeter of active thruster surface. Parallel operation of multiple thrusters has been demonstrated, allowing for thrust scalability according to mission requirements. This way, the electrospray propulsion emitters developed at MIT have the capability to deliver significant Δv to a Cubesat allowing for orbit raising from a suitable initial orbit to lunar space. Studies on the utility of an up-scaled propulsion system based on the electrospray thruster technology are presented and explored in the context of different initial orbits.

C.2 An Enabling Low-Power Magnetically Shielded Hall Thruster for Interplanetary Smallsat Missions

Ryan Conversano, Dan Goebel, and Nathan Strange
(JPL/Caltech)

Despite the growing interest in smallsats, there are no flight-qualified propulsion systems that can fit in the form-factor of smallsat-class (50–300 kg wet mass) spacecraft which can provide the large Delta-V requirements (5–10 km/s) for interplanetary science missions. While large chemical boosters can be utilized for smallsat propulsion (adding hundreds of kg's to the launch mass of the spacecraft), a low-power, long-life Hall thruster-based electric propulsion (EP) system would offer the propulsive capability to travel to deep-space targets as well as significant maneuverability (second celestial body, plane-change, orbit raising, etc.) once the spacecraft arrived at the target. This combination of propulsive capabilities is unmatched by chemical systems of the same scale, especially given the compact size and relatively low mass (including the required propellant) of modern EP systems. The Magnetically Shielded Miniature (MaSMi) Hall thruster under development at JPL is an enabling technology for deep-space smallsats. With a projected throughput of more than 100 kg of Xe based on experimental measurements taken in 2015, the current generation MaSMi-60 (which is not yet flight-optimized) has already been shown to be a leading low-power Hall thruster and a strong option for future deep-space, high Delta-V smallsat missions. In this investigation, we aim to highlight the enabling attributes of a MaSMi-based low-power EP system for smallsat applications. We will examine both solar electric propulsion (SEP) and non-solar (RTG-based) propulsion system architectures and the potential missions that these systems enable. A mission analysis will also be included to show an example of the challenging trajectories made possible by a MaSMi-based EP system applied to a smallsat-class spacecraft.

C.3 Role of small satellites in fast Mars transit

Darrin Taylor (Outerspacecolonization)

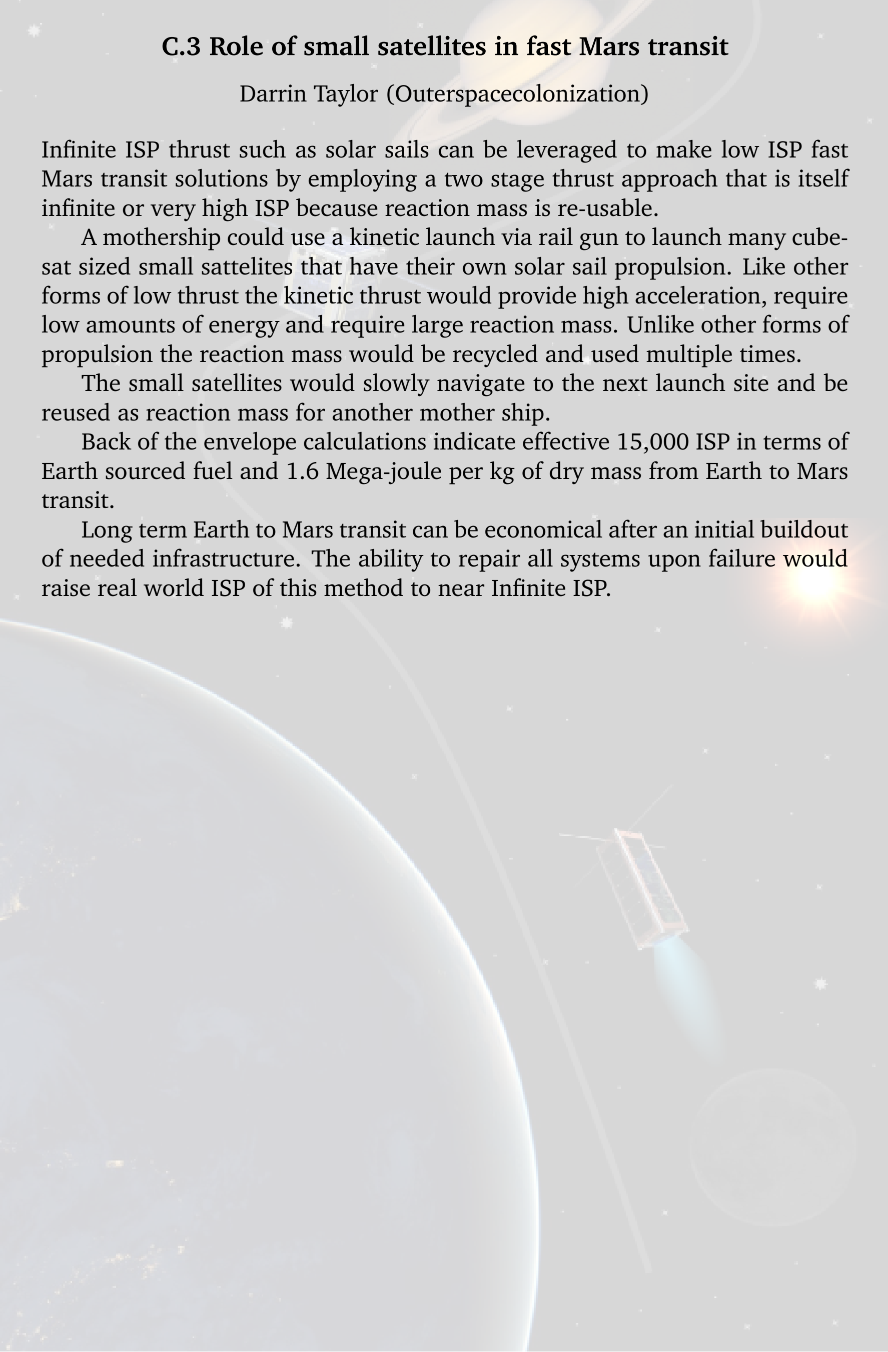
Infinite ISP thrust such as solar sails can be leveraged to make low ISP fast Mars transit solutions by employing a two stage thrust approach that is itself infinite or very high ISP because reaction mass is re-usable.

A mothership could use a kinetic launch via rail gun to launch many cubesat sized small sattelites that have their own solar sail propulsion. Like other forms of low thrust the kinetic thrust would provide high acceleration, require low amounts of energy and require large reaction mass. Unlike other forms of propulsion the reaction mass would be recycled and used multiple times.

The small satellites would slowly navigate to the next launch site and be reused as reaction mass for another mother ship.

Back of the envelope calculations indicate effective 15,000 ISP in terms of Earth sourced fuel and 1.6 Mega-joule per kg of dry mass from Earth to Mars transit.

Long term Earth to Mars transit can be economical after an initial buildout of needed infrastructure. The ability to repair all systems upon failure would raise real world ISP of this method to near Infinite ISP.



C.4 Interorbital Systems: Launch Services to LEO, Luna, and Beyond

Ronda Relich Milliron (Interorbital Systems)

The expense of buying passage for a small satellite payload is often more than a small business or an academic institution can afford, and usually more than a government or military entity would like to spend. Waiting for an opportunity to launch as a secondary payload is often a frustrating, if not endless process. Global competitions among hundreds of student satellite projects for these rare flights leave all but the one or two lucky winners without a ride to orbit. An inexpensive, dedicated launcher; an assortment of affordable small satellite kits; and low-cost, rapid-response launch services are urgently needed to create and carry small experimental, academic, government, art, and military payloads to orbit. Interorbital Systems' NEPTUNE modular rocket series: N3; N5; N9; and N35, and IOS' Personal Satellite Kits will fill those needs. For example, the N5 is designed to launch 24 picosats at a time, for as little as $8,000 each, or from $1 million for a single dedicated 30-kg payload capacity. The popularity of this new service is evidenced by Interorbtial's current orbital launch manifest of 123 picosats for upcoming sold-out LEO Missions I-V. GLXP and 'Lunar Bullet' Moon launches begin in 2017. Flight-testing continues through mid-2016 with first orbital launches beginning third quarter 2016.

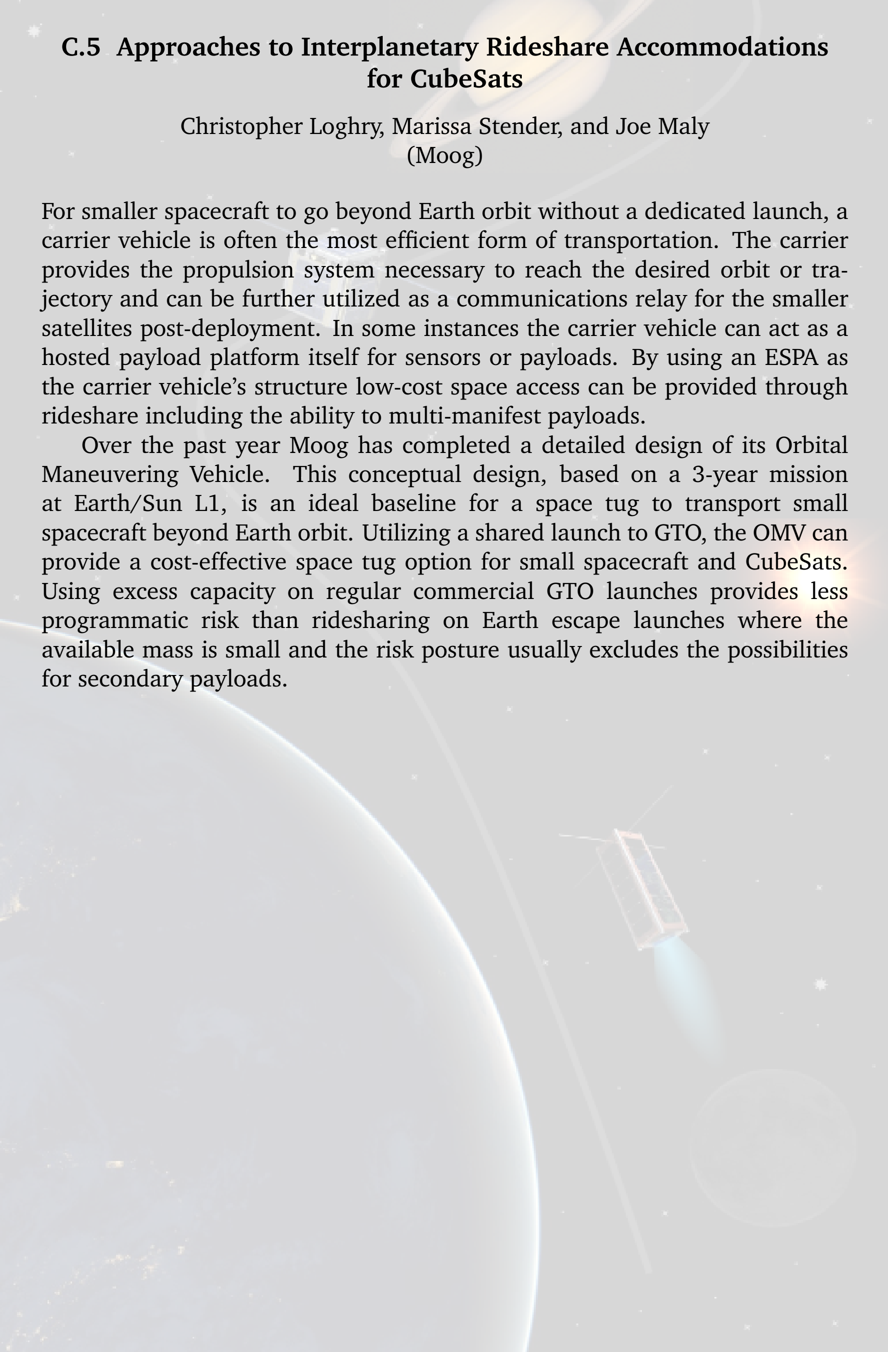
Partial Payload Manifest: UC Irvine; Google Lunar X PRIZE Teams EuroLuna, Plan B, Part-Time Scientists, and SYNERGY MOON; FPT University, Vietnam; Nanyang Technological University, Singapore; King Abdullah University (KAUST), Saudi Arabia/US; NASA IV&V Facility; Institute of Space Technology, Pakistan;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

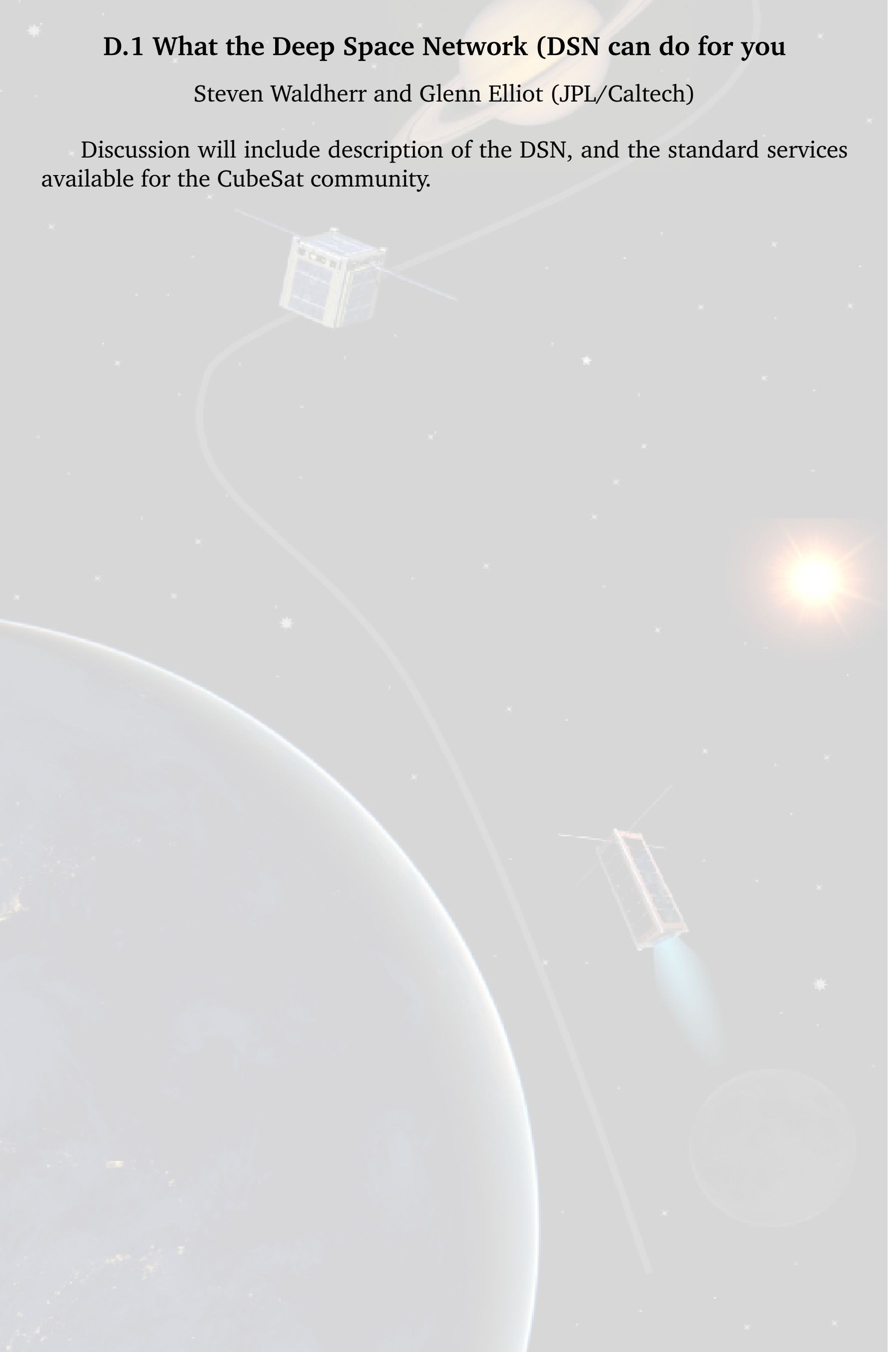
C.5 Approaches to Interplanetary Rideshare Accommodations for CubeSats

Christopher Loghry, Marissa Stender, and Joe Maly
(Moog)

For smaller spacecraft to go beyond Earth orbit without a dedicated launch, a carrier vehicle is often the most efficient form of transportation. The carrier provides the propulsion system necessary to reach the desired orbit or trajectory and can be further utilized as a communications relay for the smaller satellites post-deployment. In some instances the carrier vehicle can act as a hosted payload platform itself for sensors or payloads. By using an ESPA as the carrier vehicle's structure low-cost space access can be provided through rideshare including the ability to multi-manifest payloads.

Over the past year Moog has completed a detailed design of its Orbital Maneuvering Vehicle. This conceptual design, based on a 3-year mission at Earth/Sun L1, is an ideal baseline for a space tug to transport small spacecraft beyond Earth orbit. Utilizing a shared launch to GTO, the OMV can provide a cost-effective space tug option for small spacecraft and CubeSats. Using excess capacity on regular commercial GTO launches provides less programmatic risk than ridesharing on Earth escape launches where the available mass is small and the risk posture usually excludes the possibilities for secondary payloads.





D.1 What the Deep Space Network (DSN can do for you

Steven Waldherr and Glenn Elliot (JPL/Caltech)

Discussion will include description of the DSN, and the standard services available for the CubeSat community.

D.2 Working Toward More Affordable Deep Space Cubesat Communications: MSPA and OMSPA

Douglas S. Abraham, Bruce E. MacNeal, and David P. Heckman (JPL/Caltech)

While the cost to build and launch spacecraft tends to scale down with size, the cost to communicate does not. In fact, deep space cubesats generally need more communications capability on the ground because the capability onboard the spacecraft is so mass-, power-, and volume-constrained. Hence, an increasing number of cubesats slated for deployment beyond geosynchronous orbit are looking to NASA's Deep Space Network (DSN) for support. This presents the DSN with a two-fold challenge: (1) providing communications for the growing numbers of cubesats with a limited number of ground antennas, and (2) doing so at an attributed cost that cubesat missions can afford.

As part of its strategy for addressing this two-fold challenge, the DSN has been investigating various techniques for providing simultaneous, multi-spacecraft communications via a single antenna. Such techniques are further along for downlink than for uplink. In fact, one of the downlink techniques, Multiple Spacecraft Per Antenna (MSPA), has already been in use for more than a decade. It involves having multiple spacecraft, within an antenna's half-power beamwidth, share the antenna by transmitting at separate frequencies to separate receivers. To date, only two spacecraft have typically been serviced at a time in this manner (2-MSPA). The DSN is currently in the process of upgrading this capability to handle four spacecraft at a time (4-MSPA). In the future, it has plans to upgrade to a spacecraft capability greater than four (n-MSPA). In addition to allowing the DSN to service more missions, such MSPA techniques would also provide cubesat users with opportunities for reduced aperture fees. While NASA users do not actually pay these fees, they do count toward a mission's bottom-line cost during selection.

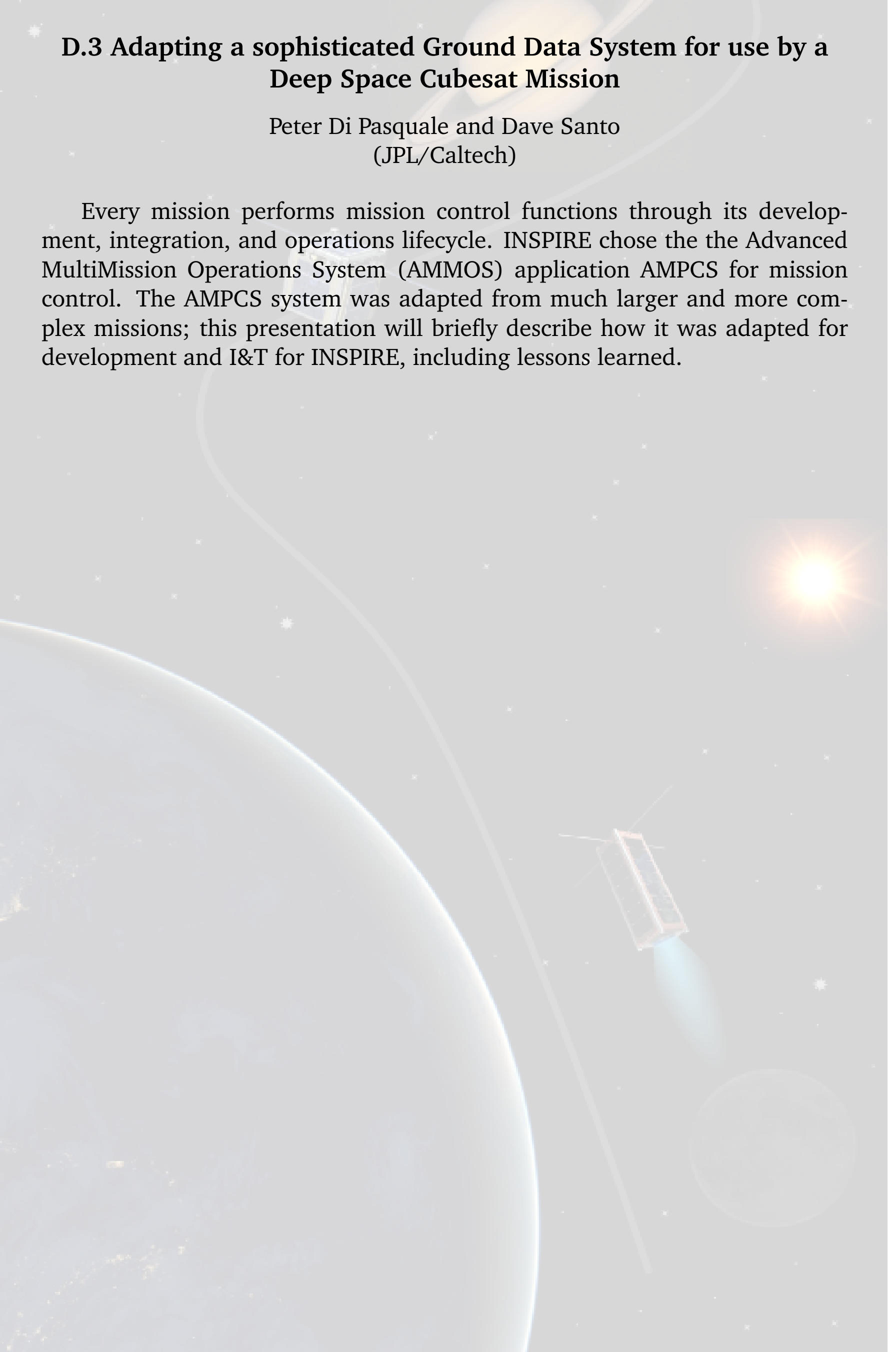
The DSN is also investigating a technique known as Opportunistic MSPA (OMSPA). In this technique, the additional receivers characteristic of MSPA are replaced by a single recorder. If one or more cubesats determine that they will be within the half-power beamwidth of another spacecraft's ground antenna, they can arrange to opportunistically transmit open-loop while the other spacecraft communicates via a traditionally scheduled link. These open-loop transmissions get captured on the antenna's recorder and can be subsequently retrieved for demodulation and decoding. Unlike MSPA, the number of OMSPA users is not constrained by the number of available receivers. And, the OMSPA user does not have to schedule the antenna pass; the user only has to know when it will be in the ground-antenna beam of a spacecraft that does have a scheduled communications link. So, if offered as a service in the future, it might involve some sort of nominal flat fee, rather than an antenna-time-based fee. The process of data recovery, however, does introduce a latency not encountered with MSPA. So, OMSPA may be better suited for routine downlink; MSPA for time-critical downlink.

Prospective cubesat users wanting to take advantage of these techniques need to pursue mission designs that maximize shared beam opportunities. Three example deep space destination classes with potential beam-sharing opportunities include: Mars and Venus missions, "flotillas" of cubesats in heliocentric Earth Trailing and Earth Leading orbits, and Sun-Earth Lagrange point 1 and 2 orbits coinciding with heliophysical and astrophysical observatory locations.

D.3 Adapting a sophisticated Ground Data System for use by a Deep Space Cubesat Mission

Peter Di Pasquale and Dave Santo
(JPL/Caltech)

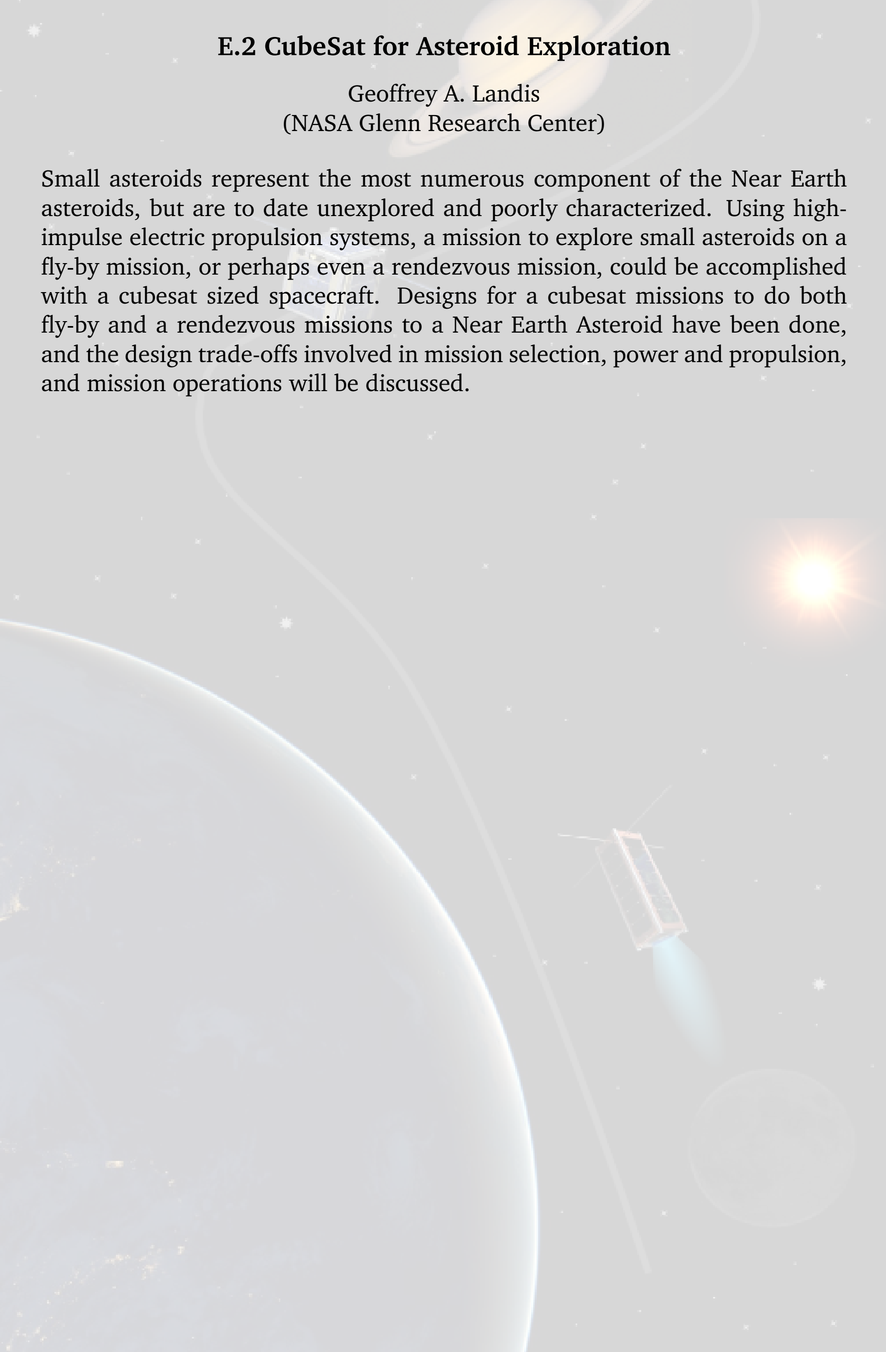
Every mission performs mission control functions through its development, integration, and operations lifecycle. INSPIRE chose the the Advanced MultiMission Operations System (AMMOS) application AMPCS for mission control. The AMPCS system was adapted from much larger and more complex missions; this presentation will briefly describe how it was adapted for development and I&T for INSPIRE, including lessons learned.



E.1 Europa Surface and Plume 3D eXplorer (ESP-3DX): A CubeSat Mission Concept to Search for Plumes on Europa

Jekan Thangavelautham, Alyssa Rhoden, James Bell, Hugh Barnaby, and the ESP-3DX CubeSat Team (Arizona State University)

Jupiter's moon Europa is hypothesized to contain a liquid-water ocean beneath a thick ice shelf. These conditions may harbor life. NASA's Europa Multi-Flyby Mission hopes to provide the most detailed view of Europa and its surface and answer some of these important questions. The spacecraft will perform 40+ flybys and map pre-targeted regions of interest at 0.5 m to 2 m/pixel. JPL has sought proposals for CubeSats that would be carried by the main spacecraft and dropped off during the flybys. A CubeSat strongly complements the capabilities of the Multi-Flyby spacecraft. It can perform high risks missions at low-altitudes and provide science data from a different vantages point. However, the conditions in the vicinity of Europa are extremely challenging due to the high-radiation around Jupiter, the low solar insolation of 50 W/m2 and low temperatures of -150 to -200 oC. Arizona State University (ASU) has proposed a 3U CubeSat called Europa Surface and Plume 3D eXplorer (ESP-3DX) equipped with a pair of radiation hardened stereo cameras and radiation monitoring sensors. ESP-3DX will be deployed on a 10 hour mission when the main flyby spacecraft is on a 25 km flyby over Europa and have the option to target specific sites of science interest. ESP-3DX will use its on-board cold gas thrusters to descend to within 3-12 km of Europa's surface. The CubeSat will track linaes along the surface of Europa (long cracks in the ice) to look for evidence of plumes or past plume deposits. In addition, the CubeSat will obtain 0.3 m/pixel detailed imagery useful for landing site reconnaissance and for validating flyby spacecraft images. Images and science data will be transmitted at 2-8 MBps using a version of the JPL IRIS X-band radio. The science phase will last 15-20 minutes and optionally culminate in a surface impact monitored by the Multi-Flyby spacecraft. ESP-3DX will utilize primary batteries for power and reuse waste heat to maintain operational temperatures using a metabolic thermal control system. Significant work will be required to miniaturize and radiation harden critical components on the CubeSat but a credible pathway has been shown for developing this technology for a future mission.



E.2 CubeSat for Asteroid Exploration

Geoffrey A. Landis
(NASA Glenn Research Center)

Small asteroids represent the most numerous component of the Near Earth asteroids, but are to date unexplored and poorly characterized. Using high-impulse electric propulsion systems, a mission to explore small asteroids on a fly-by mission, or perhaps even a rendezvous mission, could be accomplished with a cubesat sized spacecraft. Designs for a cubesat missions to do both fly-by and a rendezvous missions to a Near Earth Asteroid have been done, and the design trade-offs involved in mission selection, power and propulsion, and mission operations will be discussed.

E.3 Constellations of CubeSats

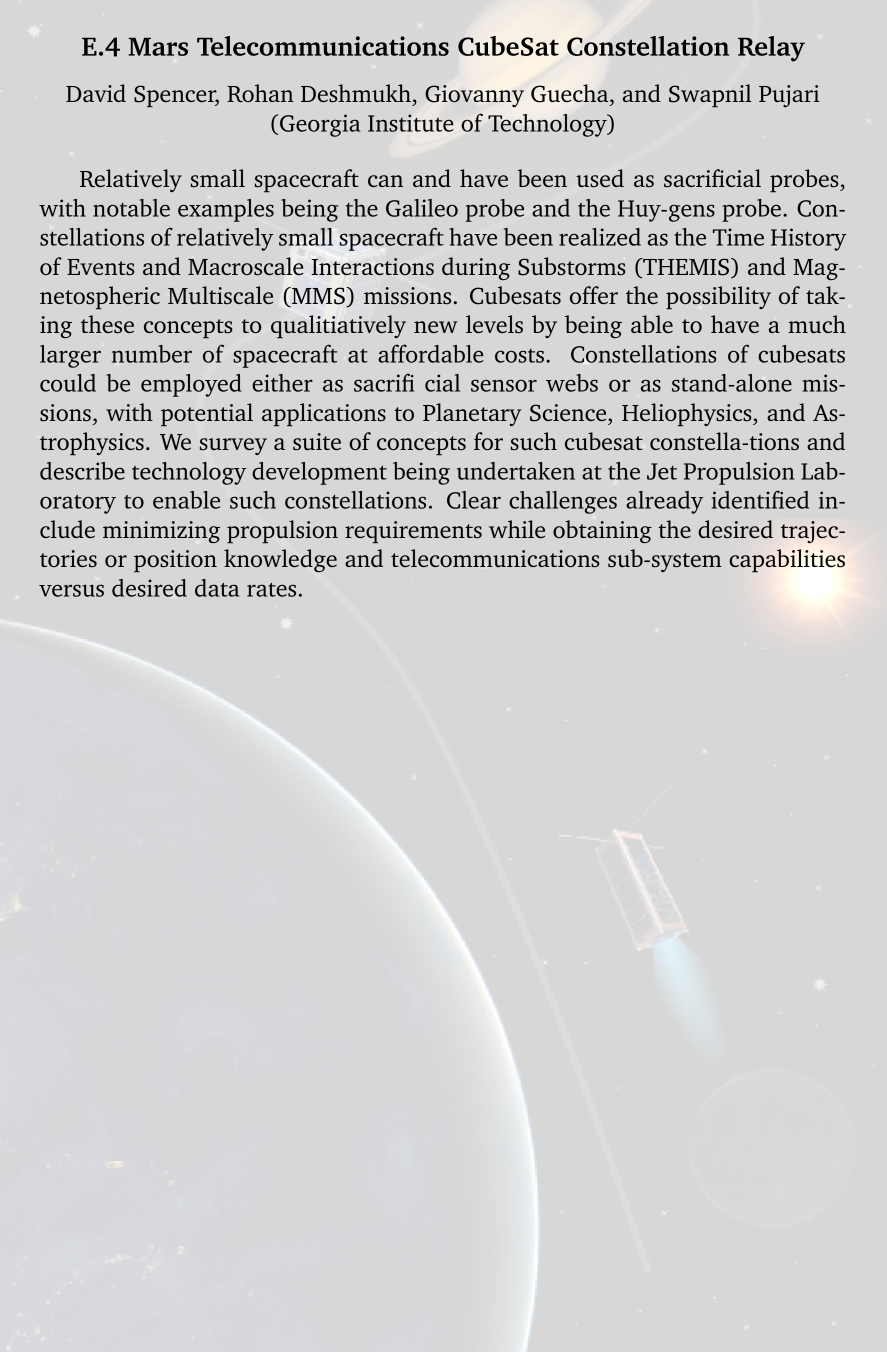
Joseph Lazio, Julie Castillo-Rogez, Konstantin Belov, Steve Chien, Loren Clare, and Jay Wyatt (JPL/Caltech)

Relatively small spacecraft can and have been used as sacrificial probes, with notable examples being the Galileo probe and the Huy-gens probe. Constellations of relatively small spacecraft have been realized as the Time History of Events and Macroscale Interactions during Substorms (THEMIS) and Magnetospheric Multiscale (MMS) missions. Cubesats offer the possibility of taking these concepts to qualitatively new levels by being able to have a much larger number of spacecraft at affordable costs. Constellations of cubesats could be employed either as sacrificial sensor webs or as stand-alone missions, with potential applications to Planetary Science, Heliophysics, and Astrophysics. We survey a suite of concepts for such cubesat constellations and describe technology development being undertaken at the Jet Propulsion Laboratory to enable such constellations. Clear challenges already identified include minimizing propulsion requirements while obtaining the desired trajectories or position knowledge and telecommunications sub-system capabilities versus desired data rates.

E.4 Mars Telecommunications CubeSat Constellation Relay

David Spencer, Rohan Deshmukh, Giovanny Guecha, and Swapnil Pujari
(Georgia Institute of Technology)

Relatively small spacecraft can and have been used as sacrificial probes, with notable examples being the Galileo probe and the Huy-gens probe. Constellations of relatively small spacecraft have been realized as the Time History of Events and Macroscale Interactions during Substorms (THEMIS) and Magnetospheric Multiscale (MMS) missions. Cubesats offer the possibility of taking these concepts to qualitiatively new levels by being able to have a much larger number of spacecraft at affordable costs. Constellations of cubesats could be employed either as sacrificial sensor webs or as stand-alone missions, with potential applications to Planetary Science, Heliophysics, and Astrophysics. We survey a suite of concepts for such cubesat constella-tions and describe technology development being undertaken at the Jet Propulsion Laboratory to enable such constellations. Clear challenges already identified include minimizing propulsion requirements while obtaining the desired trajectories or position knowledge and telecommunications sub-system capabilities versus desired data rates.



E.5 Evaluation of stable periodic orbits about non-spherical objects

Jason C. Swenson, Marcus J. Holzinger, and E. Glenn Lightsey
(Georgia Institute of Technology)

Planetoids in our solar system are non-spherical with non-uniform mass distribution and nonhomogeneous density. While an approximation of the trajectory and nonlinear dynamics for a small satellite about an arbitrary object-of-interest is generally understood, the optimal thrust required to transfer between stable, periodic orbit solutions is not well established. This research first focuses on the validation of a developed hybrid orbit propagator based on State Transitions Matrices and Gauss Variation of Parameters. A constrained minimization problem is then solved to discover optimal thrust control inputs and state vector uncertainties for small satellite trajectory transfers about non-spherical planetoids, given a closed set of periodic orbits.

F.1 Spacecraft/Rover Hyprids for the Exploration of Small Solar System Bodies

Benjamin Hockman and Marco Pavone (Stanford University)
Julie Castillo-Rogez, Andreas Frick, Robert Reid, and Issa Nesnas (JPL/Caltech)

The future in-situ exploration of small Solar System bodies requires robotic platforms capable of controlled surface mobility. In the microgravity environment of small bodies such as asteroids, comets or small icy moons, conventional wheeled rovers are quite ineffective due to the low frictional forces on the ground. Through a joint collaboration between Stanford University, JPL, and MIT under the NIAC program, we have been investigating microgravity mobility using hopping/tumbling platforms. We present a minimalistic, internally-actuated spacecraft/rover hybrid that is capable of controlled hopping for large surface coverage and tumbling for fine mobility and instrument pointing. Specifically, the hybrids apply torques to internal flywheels to transfer angular momentum to the external structure. For a grounded rover, this gives rise to controllable ground reaction forces that propel the hybrid along desired trajectories. Such a mobility approach is critically enabled by the microgravity environment of small bodies, whereby small surface contact forces can produce long-range ballistic flight. We have demonstrated controlled mobility in simulation, in a high fidelity microgravity test bed, and onboard NASA parabolic flights.

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

Part of this work has been carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract to NASA. Government sponsorship acknowledged.

F.2 Using Spatial Heterodyne Spectrometers for high spectral resolution observation of extended sources in future interplanetary smallsats

Sona Hosseini (JPL/Caltech)

The most commonly used technique for high spectral resolution (R) studies are grating spectrometers. These instruments are both broadband and high R, but they have small FOV and relatively low tendue and have to be paired with large aperture telescopes such Keck (10m), Hubble (2.4m) or JWST (6.5m). Fabry-Prot Interferometers (FPI) and FTS are the other best known types of high étendue, high R spectrometers used in astronomy. But in the use of transmitting optics becomes a limiting challenge, where transmission of lenses and windows drops. In addition the opto-mechnical tolerances becomes challenging for the FTS and the piezo-electrically crystal-tuned FPI, which must maintain parallelism between two flat surfaces, to accuracies of fractions of a wavelength, while changing their separation. Failure to do so quickly results in loss of interference. In addition in shorter wavelengths going from NUV to FUV and EUV the use of reflecting rather than transmitting optics is necessary, especially below 130 nm where transmission of lenses and windows drops rapidly. Spatial Heterodyne Spectrometer is a relatively novel candidate for high étendue, high R spectroscopy in compact low cost, low-mass, low-power architecture using no or small aperture telescope for UV to IR wavelengths. SHS based technique, have been making headway as an alternative to both FPIs and FTSs, and can be made extremely compact in a reflective design and have no moving parts for narrow bandpasses. For UV observation, currently HST is the only telescope capable of collecting the necessary observations and the next major UV space telescope might be able to fly in 10 years or more. SHS instrument can quickly fill the technology gap for UV space spectrometers.

Developing the SHS instrument has a wider significance to astrophysics and planetary science. SHS provides integrated spectra at high R, over a wide FOV in compact designs in which it offers the ability to make key science measurements for a variety of planetary targets. SHS could be implemented on a dedicated SmallSat or ISS that can sit and stare at its target for long duration of time that cannot be done from the ground or on big missions. SmallSats are lower cost, faster to build, relatively easy to correct and upgrade. High R spectrometers are usually limited by the telescope aperture size and complicated opto-mechanical tolerances but that's not the case for SHS.

F.3 Small Gravity Geophysics Inside CubeSat Centrifuge

Erik Asphaug, Jekan Thangavelautham, Aman Chandra,
and Laksh Raura (Arizona State University)

Considerable research attention is paid to the zero-G environment of space, but equally important and more fundamentally baffling is the microgravity environment relevant to comets, asteroids, planetesimals and small moons. Understanding such environments is vital to understanding planet formation and evolution, and to overcoming the technological hurdles of small body exploration. The gravity field around a small planetary body is measurable and constant, but less than one percent the gravity of Earth. For reference the surface gravity of a 1 km asteroid is about 0.0001 G. Astronauts would feel 'weightless' in such environments, yet at the end of the day, all of their belongings would be on the floor. Do melted planetesimals differentiate into an iron core and a rocky mantle, or is their gravity and internal pressure too weak? At what size does gravity overcome surface tension and other forces? Do landslides occur on small granular asteroids? Evidently, but with ground movements of only a few cm/s is the physics the same as on the Moon and on Earth? Does the Brazil Nut Effect segregate an asteroid's components by size? In a separate abstract (Chandra et al.) we describe our ongoing development of AOSAT-1, which is a 3U CubeSat centrifuge spinning at $\sim$1 rpm to attain the equivalent gravity of a 100 m diameter asteroid; its experimental chamber is designed to conduct experiments into meteorite regolith. Here we describe several additional concept payloads, representing relatively small modifications to AOSAT-1, for use in mitigating the risks of more costly missions (testing lander and sampler designs), accelerating the development of instrument or method prototypes, advancing capabilities in microgravity operations, developing novel technologies of in-situ resource extraction, and exploring the behavior of material properties and mixed liquid dynamics in space. We emphasize environments where access to non-human-tended environments is a priority, either for cost or schedule, or because the experiments may be hazardous to astronauts. We emphasizing experiments that will function with limited control from the ground, and with limited power and availability of consumables.

F.4 ASU Interplanetary CubeSat

Graham Dektor, Nalik Kenia, Jehan Thanga, Erik Asphaug
(Arizona State University)

The Martian Moon Phobos holds many unanswered questions that may provide clues to the origin of Mars. The moon exhibits unique surface features, particularly striations due to being within the Mars Roche limit. Phobos has been proposed as potential, low delta V stop-over site for future human missions to Mars. Using Phobos, it has been suggested that future human missions could tele-operate Mars assets or develop infrastructure for eventual human landing on Mars. Considering the strategic importance of Phobos to future Mars exploration, there has been little known about Phobos or its surface. Soviet Union's Phobos lander launched in the late 1980's was lost within 30 minutes of landing on the Moon's surface.

The objective of Devil's LOGIC, the Low Orbit Geology Imaging Cubesat, is to capture into the Mars System and return visible and thermal images of the Martian moon Phobos.

LOGIC, a 6U CubeSat comprised primarily of COTS components (Commercial Off The Shelf), will accomplish its mission in four phases: Deployment, Transit, Mars Capture and Science Operations. The satellite will be deployed on an Earth escape orbit to Mars. LOGIC will communicate with the Deep Space Network (DSN) utilizing IRIS X-band radio and reflect array. Mars capture is to be achieved utilizing a green monopropellant thruster to perform a series of impulsive maneuvers. LOGIC will capture into a highly elliptical orbit utilizing this method, and perform 3 months of aero braking maneuvers to reduce its apoapse to match that of Phobos. The final phase of the mission will begin as science operations commence when LOGIC is within 50 km of Phobos. Observation opportunities will be available during the elliptical orbit and X-band communication will be used to relay science data. Electric propulsion will be available for maneuvers and orbit circularization but not vital to mission success, as multiple interactions within the range of the science payload will be achievable from the elliptical orbit. The CubeSat will be able to get within reach of Phobos to obtain thermal images at resolution higher than what's currently available of at least half the Moon's surface. An extended mission offers full coverage of Phobos.

F.5 Sampling Venus' atmosphere with a low-cost, fre-flying Smallsat prove

A. Freeman (JPL/Caltech)

The Venus Exploration Advisory Group (VEXAG) has elevated to a very high priority the need to measure the relative abundances of Neon, Argon, Helium, Krypton and other noble gases in the planetary science communitys efforts to understand how Venus atmosphere formed and has evolved. The underlying objectives are to determine if Venus and Earth formed from the same mix of solar nebular ingredients, and whether comets played a substantial role in delivering volatiles. To be truly representative of the noble gases and their isotopic ratios, a sample of the atmosphere has to be acquired where the atmosphere is well-mixed: at an altitude below the homopause, which for Venus is around 120 km.

This paper describes a novel, low-cost, Smallsat architecture for a standalone mission to sample the noble gases and their isotopic ratios at Venus. Sampling is achieved by a compact, ion-trap mass spectrometer incorporated into a small probe that skims through the atmosphere, targeting a closest approach altitude above the surface below the nominal 120 km. Following acquisition, the gas sample is analyzed over a period of 100 minutes, then results are relayed via a UHF comm link to the microsat carrier spacecraft that escorted the atmospheric entry probe to Venus. Data is then relayed back to Earth via an X-Band downlink.

The Venus probe + carrier spacecraft are launched together on a Type II trajectory towards Venus, on a dedicated Pegasus launch vehicle with a STAR 27 motor developed by Orbital Sciences Corporation. The combined probe + carrier spacecraft mass is estimated at less than 55 kg. The compact mass spectrometer instrument mass is 8 kg. En route to Venus the carrier spacecraft executes pre-planned TCM maneuvers for a total Delta-V of about a hundred m/s. On approach, the carrier spacecraft spins up to rotate at 10 rpm, then releases the probe on its path to skim through the atmosphere. The carrier spacecraft then executes a small maneuver (with a few m/s Delta-V) to fly past Venus above the atmosphere. Following the probe skim-through and data analysis, results are returned to Earth via a UHF/X-Band relay, similar to that developed for MarCO.

Carrier spacecraft and probe costs are kept low by using avionics, telecom and other subsystems developed for other NASA/JPL planetary cubesat missions, including INSPIRE and MarCO. Launch windows for Type I or II trajectories to Venus, which have the lower transfer energies, fewest maneuvers, and shorter transit time, occur roughly every 19 months.

The work described here was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

G.1 Reference CubeSat Core Avionics for Deep Space Science

Julie Castillo-Rogez (JPL/Caltech)

The availability of launches to deep space planned with the maiden flight of the Space Launch System in 2018 has prompted the development of several highly capable 6U CubeSat flight systems. This presentation focuses on the NEAScout and Lunar Flashlight flight systems that share common avionics but use different propulsion techniques. Science drivers have led to the design and ongoing implementation of highly capable computing capabilities, novel software for science extraction, fine pointing performance, and telecommunications/navigation. They are also pushing new approaches to science operations. The core flight system has been designed in a modular manner with in mind the prospect to accommodate a variety of instruments and propulsion systems. The two types of propulsion being matured and tested for these missions are a mid-sized solar sail (NEAScout) and chemical propulsion (Lunar Flashlight), as well as cold gas reaction control systems, which together encompass a broad range of ΔV, Isp, and lifetime performance.

This presentation will report on the capabilities offered by the core avionics for these missions and present follow on planetary and heliophysics applications that would benefit from these ongoing development efforts.

Part of this work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract to NASA. Government sponsorship acknowledged.

G.2 Rad Hard and CryoElectronics for CubeSats in Jovian Radiation Environments

Robert Frampton and Leora Peltz
(The Boeing Company)

A Europa mission has been selected by NASA as the next flagship mission, for launch as soon as 2022. A mission to Europa may include cubesats released from the flagship spacecraft. These cubesats would be too small to carry heavy shielding or sufficient batteries for heaters to keep electronics warm. They would be required to have a lifetime longer than a few hours; therefore, the electronics would need to be designed to operate at the extreme cold temperatures and in the Jovian extreme radiation environment.

Europa has extreme environmental conditions, with a surface temperature varying from a low of 50 Kelvin up to 125 Kelvin, with a mean temperature of around 100 Kelvin. We can expect similar orbital temperatures. Europa also has an extreme radiation environment, as high as 20 Mrad-Total Ionizing Dose (TID) per month. These are harsh and challenging environments for electronics circuitry. SiGe and GaN technologies are both particularly suited to meet these demands. Both SiGe and GaN are wide-band-gap materials, giving them inherent radiation tolerance (rad-hard by technology). The SiGe will operate over a wide range of temperatures: down to 43 Kelvin (-230 deg C) without “warm boxes”, and up to 398 Kelvin (+125 deg C), in normal operation. The performance characteristics of SiGe devices vary gracefully over this extreme temperature range, with no evidence of abrupt “killer” phenomena. The structure of SiGe devices also confers a “free perk” – multi-Mrad total dose hardness, even with no intentional hardening-by-design. GaN devices are suitable for high voltage and high power circuits, such as needed fields-and-particles instruments and S-Band transmitter.

Designing SiGe chips for these extreme environments, translated into device parameters, require new design rules. Device models in design tools (Cadence) must be extended, calibrated upon experimental data. Packaging design must account for the different thermal coefficients of die, casing and bonding materials, and the variations in physical properties of these materials over the temperature range.

SiGe is obtained by introducing a small (5%-15%) amount of germanium (Ge) in the silicon (Si) lattice. Si and Ge are “almost-but-not-perfect match”, and the resulting lattice is stressed. After years of consistent research, semiconductor manufacturers (primarily IBM and TowerJAZZ) have developed a reliable fabrication platform, compatible with standard Si integrated circuits fabrications, which offers low cost and high integration. The lattice stresses in SiGe bring desirable properties to SiGe devices. Higher operating speeds are possible – SiGe technology is well accepted in high-speed communication circuits. And, important for our applications, SiGe devices can operate reliably in the extreme cold typical of Europa and the other icy satellites of the outer solar system, without carrier freeze-out.

Radiation hardening of electronic circuits can be accomplished by a combination of five methods: (1) radiation hardening by technology is achieved utilizing wide band-gap materials such as SiGe, SiC, and GaN, which have innate radiation tolerance (use of SiGe-on-Insulator provides further radiation tolerance); (2) local spot-shielding using proven low-Z materials; (3) rad-hard-by-design at the device level, by using design techniques that involve employing unique geometries of the device and isolation trenches in the device to contain charge-bursts created by the radiation; (4) rad-hard design at the circuit level by including built-in redundancy and a compensating circuit; and (5) error-detecting-andcorrecting (EDAC) module and code.

This paper presents the radiation environments for cubesats in orbit or penetrators at the surface of Europa. It presents design characteristics for Silicon-Germanium circuitry for operating low temperature (to 40 Kelvin) and high radiation environments, along with preliminary test results. Further, the paper proposes a radiation testing regime that would expose the electronics to an equivalent radiation dose as would be experienced during a 90-day mission at Europa. This testing regime includes sequential exposure to high energy electrons, protons, and heavy ions, involving combined radiation dosage at cyclotron facilities, and exposure to Van Allen Belt radiation in geosynchronous transfer orbit.

GaN devices are being developed by HRL Laboratories in Malibu, which has a GaN foundry. This project addresses NASA Technology Roadmap Goal 8.1.2 Electronics: Radiation-hardened, extreme environment capable, and data processing electronics with reduced volume, mass, and power.

G.3 Reliable Software for an Interplanetary CubeSat

Carl Brandon
(Vermont Technical College)

Vermont Technical College CubeSat Lab is developing the flight software for the Lunar IceCube, a 6U (10cm x 20cm x 30cm, 14kg) CubeSat that is manifested on the Space Launch System (SLS) EM-1 flight to the Moon in 2018. This is a self-propelled CubeSat with an iodine ion drive that will be used to go from the SLS drop off point into orbit around the Moon. Lunar IceCube will then survey the Moon for water ice, vapor and other volatiles with its IR spectrometer. The rest of the team for Lunar IceCube is Morehead State University (the PI), Catholic University & NASA JPL (Science PI), Goddard Space Flight Center (IR spectrometer and navigation), Busek (iodine ion engine) and NASA JPL (Iris 2 X-band data and navigation radio and the Deep Space Network, which we will use). Previous CubeSat missions have almost all been programmed in the very error prone C language. We will be using SPARK/Ada, the most reliable software system available. Ada has been used for many NASA missions (Cassini, Space Shuttle, ISS, Chandra, EOS, Terra, GOES, CloudSat, QuikSCAT, Oersted and many others), virtually all European Space Agency missions and well as launch vehicles Ariane IV & V, Atlas V, Delta II & IV (used for the first Orion test). Ada is also used in all commercial airline avionics and air traffic control systems. SPARK, a set of static analysis tools which greatly increases the reliability of Ada was used in our Vermont Lunar CubeSat, the first spacecraft of any kind to use SPARK. SPARK is used in the Airbus engine control system and the new UK air traffic control system.

We have shown the reliability of SPARK in our Vermont Lunar CubeSat. This CubeSat operated from launch, November, 2013 for two years and two days until reentry on November 21, 2015. We were the first satellite launched from a University in New England, and the only successful satellite from a university in the entire Northeast United States. Of the 12 CubeSats on the ELaNa IV launch, ours was the only one fully successful. Eight were never heard from, two had partial contact for a week and one operated for four months. We believe software errors are the most likely cause of the failures. SPARK/Ada has 1% of the C error rate. We are developing CubedOS (http://cubesatlab.org/CubedOS.jsp) as a basis for Lunar IceCube and other CubeSat flight control software.

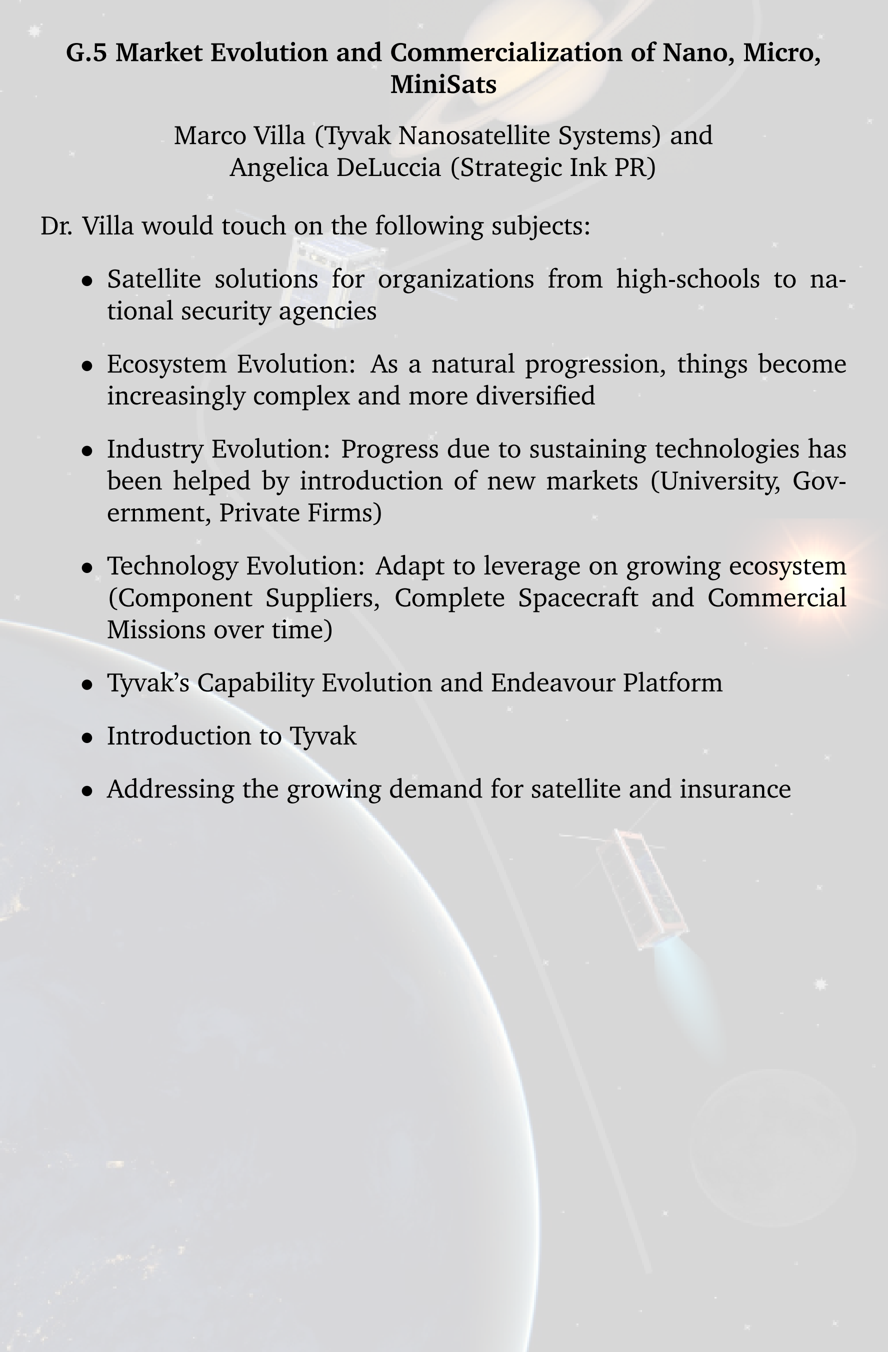
G.4 Characterization of the BCT Nano Star Tracker Performance

Kevin Lo and Laura Jones
(JPL/Caltech)

The Blue Canyon Technologies (BCT) Nano star tracker is one of the few COTS star trackers for CubeSats on the market that has a technological readiness level (TRL) of 6 or higher. This tracker is also bundled in the BCT XACT, an integrated attitude control system (ACS) unit that provides all ACS sensors, actuators, and algorithms to complete a mission. Many missions are now baselining the XACT or standalone Nano star tracker and relying on its performance to enable their mission. Thus, it is important to understand the characteristics of the star tracker.

The BCT Nano star tracker boresight performance is characterized using two different telescopes at JPL's Table Mountain Observatory (TMO). The noise equivalent error (NEA), low frequency spatial error (LFE), high frequency spatial error (HFE), total accuracy, and slew rate limits of the star tracker were tested during various nights at TMO. The star tracker NEA, LFE, HFE, and total accuracy tests were performed on the 0.6m telescope, which uses an equatorial mount but can only track up to 1 deg/s in each axis. The tracker slew rate limits were tested on the Optical Communications Telescope Laboratory (OCTL), which uses an azimuth/elevation mount to slew up to 10 deg/s in each axis.

The focus of this study is to provide an independent assessment of the star tracker's performance capabilities, which then can also be used in future star tracker models for simulations with higher accuracy. Understanding the star tracker performance will enable a class of CubeSat missions that rely on tighter pointing requirements.



G.5 Market Evolution and Commercialization of Nano, Micro, MiniSats

Marco Villa (Tyvak Nanosatellite Systems) and
Angelica DeLuccia (Strategic Ink PR)

Dr. Villa would touch on the following subjects:

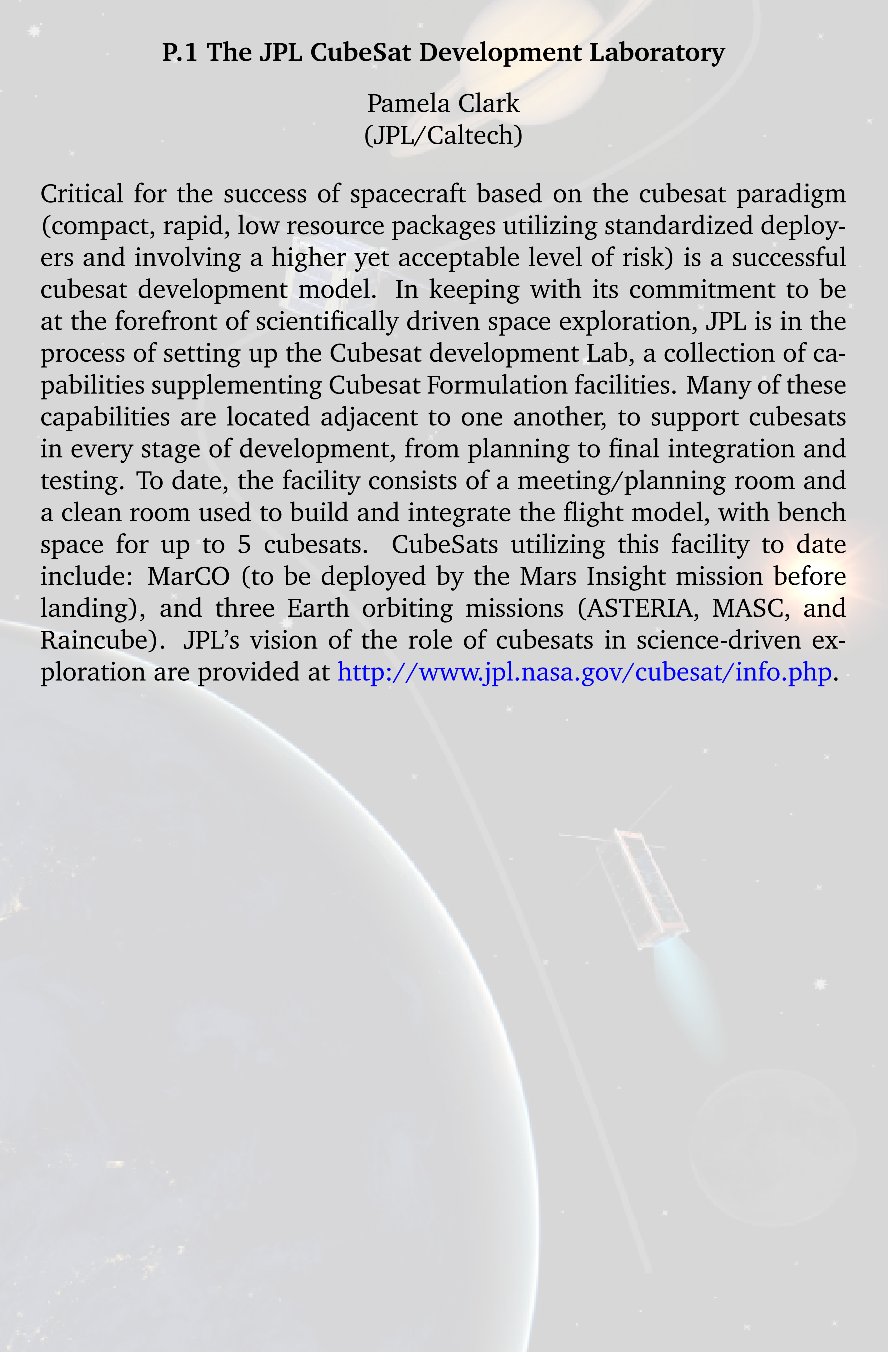
- Satellite solutions for organizations from high-schools to national security agencies
- Ecosystem Evolution: As a natural progression, things become increasingly complex and more diversified
- Industry Evolution: Progress due to sustaining technologies has been helped by introduction of new markets (University, Government, Private Firms)
- Technology Evolution: Adapt to leverage on growing ecosystem (Component Suppliers, Complete Spacecraft and Commercial Missions over time)
- Tyvak's Capability Evolution and Endeavour Platform
- Introduction to Tyvak
- Addressing the growing demand for satellite and insurance

G.6 Moving Toward a More Capable Small Satellite Bus for Interplanetary Missions

E. Glenn Lightsey
(Georgia Institute of Technology)

Small satellites, including CubeSats, are well known for their potential to provide value added science to interplanetary missions as rideshares on larger vehicles. However, there is a known technology gap between the current capabilities of many small satellites and what is needed to support a high profile multi-year interplanetary exploration mission.

This presentation will focus on 3 technology areas that are in need of further development to provide more reliable small satellite buses intended for operation in challenging environments. The topics selected for study are radiation tolerance, thermal stability, and communications. In each case, the state of the art and current capabilities will be briefly surveyed and compared to the needs for a typical multi-year interplanetary science mission. Possible design solutions and technology development plans will be recommended as a means of motivating further research into high return areas for advancing small satellite capabilities to support future interplanetary space missions.



P.1 The JPL CubeSat Development Laboratory

Pamela Clark
(JPL/Caltech)

Critical for the success of spacecraft based on the cubesat paradigm (compact, rapid, low resource packages utilizing standardized deployers and involving a higher yet acceptable level of risk) is a successful cubesat development model. In keeping with its commitment to be at the forefront of scientifically driven space exploration, JPL is in the process of setting up the Cubesat development Lab, a collection of capabilities supplementing Cubesat Formulation facilities. Many of these capabilities are located adjacent to one another, to support cubesats in every stage of development, from planning to final integration and testing. To date, the facility consists of a meeting/planning room and a clean room used to build and integrate the flight model, with bench space for up to 5 cubesats. CubeSats utilizing this facility to date include: MarCO (to be deployed by the Mars Insight mission before landing), and three Earth orbiting missions (ASTERIA, MASC, and Raincube). JPL's vision of the role of cubesats in science-driven exploration are provided at http://www.jpl.nasa.gov/cubesat/info.php.

P.2 Inflatable Antennas for CubeSats and Small Spacecraft: Advances in Shape Retention and Stowage

Aman Chandra (Arizona State University)
and Alessandra Babuscia (JPL/Caltech)

CubeSats and small spacecraft offer a low-cost approach to interplanetary space exploration thanks to reduced launch mass and volume. However this has often meant reduced capabilities, particularly low communication data rates. Low-mass deployable structures with large surface area have the potential to enable CubeSats and small spacecraft to match or exceed communication data rates of conventional large spacecraft. Inflatable structures such as parabolic reflectors hold considerable promise with a packing efficiency up to 20:1 and about one tenth the mass of conventional deployable technologies. Inflatable reflectors are designed for operating in the X-band and provide high gain (34.4 dB peak gain at 8.4 Ghz) which could enable high data rates (Mbits/s) in low earth orbits and beyond. The proposed inflatable antenna would deploy from a 0.5U volume (5 cm x 10 cm x 10 cm). Work has progressed in demonstrating chemical sublimate based inflation coupled with rigidization using UV resin in a high vacuum. A metric has been developed to quantify the extent to which desired surface shapes are achieved before and after the inflation and rigidization process. Our work now addresses fundamental challenges of eliminating wrinkles, enabling controlled shaped retention and compact stowage. Finite Element mesh solvers have been developed to simulate membrane deflection behaviour and visualize inflated shapes at various stages of deployment. The analysis was aimed at obtaining a design that would provide for high packing efficiency in stowed state and reliable inflation. Membrane prototypes have been design and manufactured with flexible envelopes containing liquid UV resin which take the inflatable's shape to form a hard support structure when rigidized. Results obtained through simulation support photogrammetric surface shape measurements. With these results in hand, there is a promising pathway towards realizing an inflatable antenna demonstrator mission.

P.3 Asteroid Origins Satellite I: An Orbit Planetary Science Laboratory

Andrew Thoesen, Aman Chandra, Laksh Raura, Andrew Warrent,
Erkik Asphaug, and Jekan Thangavelautham
(Arizona State University)

Exploration of comets and asteroids can give insight into the creation of the solar system, into the formation of Earth and the origins of the building blocks of life. However, surface exploration of asteroids and comets remains a daunting challenge due to their low gravity and unknown surface conditions. This has resulted in loss of several landers or shortened missions. Fundamental studies are required to obtain better understanding of the material surface properties and physical models of these small bodies. Sending a spacecraft to an asteroid surface mission is necessarily fraught with high risk and cost. Our proposed mission, Asteroid Origins Satellite (AOSAT-1) will simulate asteroid surface condition in Earth orbit using a CubeSat centrifuge laboratory. Such a capability couldn't be realized on the International Space Station, due to the effects of aerodynamic drag. The CubeSat will be a standard 3U platform and will carry crushed meteorite particles (the remnants of asteroid regolith). The spacecraft will operate in two modes: a stationary mode to characterize regolith accretion in the formation of asteroids and a centrifuge mode that will simulate gravity on asteroid surface less than 1 km in diameter. This work provides an overview of the design and development of critical subsystems realized for the mission. The spacecraft has been designed to gather regolith accretion data in the form of high resolution images which are processed on board using a series of smart particle detection algorithms to identify location in three-dimensions and scale of accumulation. The on board processing will enable the missions to be accomplished using a UHF data link, with selective downloading of high-resolution images. It is hoped AOSAT 1 will become a model for building CubeSat laboratories to perform science experiments in orbit. The mission has been selected through NASA's CLI (CubeSat Launch Initiative) and is scheduled for launch in 2017.

P.4 Logic and Architecture for Interactive Network of Communicating Intelligent Agents (People, Robots, Spacecraft) for Mars 2020

Jonathan Vos Post
(Caltech Life Alumnus)

In the thirst three ISSCs (2013, 2014, 2015) I presented Five papers or Posters. Three of these involved chronological estimates for Freeman Dyson's Noah's Ark Egg Strategy for biorobotic exploration followed by human colonization and cosmic migration. His approach uses a robustly distributed approach to asteroids, outer planet moons, Kuiper Belt, Oort cloud, an adjacent Oort cloud around another star. This 2016 paper provides a framework for formal Risk Assessment of Dyson's Grand Strategy.

This framework assumes:

1. Uncertainties in the chronology (both absolute and relative dates);
2. Uncertainties in scientific knowledge;
3. Uncertainties in bioengineering and space technologies' implementation; and
4. A methodology updating Decision Analysis tree of sub-scenarios (Algorithmic evaluation of tree node probability and cost/reward.

P.5 Next Generation of Telecom Web Services for CubeSat Scheduling

Mark Johnston and Carlyn Lee
(JPL/Caltech)

In this study we describe a software architecture to deliver tools for rapid spacecraft (or CubeSat) planning and scheduling with applicability to design and analysis. We implemented web-based mission operations services to analyze potential scheduling opportunities using Representational State Transfer (REST) Application Programming Interfaces (APIs) for (1) geometric visibility analysis and (2) link budget analysis. These APIs can be made available for other software tools to use, and we have prototyped modular use of these APIs with visualization tools and Liferay portlets. We estimate link performances for various cubesat radio transceiver profiles from different ground antennas over various time frames and evaluate different scheduling opportunities, taking into account both geometric visibility and recommended data rates. Future plans include analyzing tradeoff opportunities for multiple cubesats to make optimal use of limited communications network access.

8. Social Program

Dinner Reception (April 25th)
Dinner is included in the cost of registration for all conference attendees at 6:00 pm on Monday, April 25th in the covered outdoor area opposite the exhibitor area. Meals can also be purchased for guests of attendees. All participants are encouraged to attend!

Acknowledgments

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— A special thanks to all our volunteers!

— Thank you to our exhibitors and sponsors.

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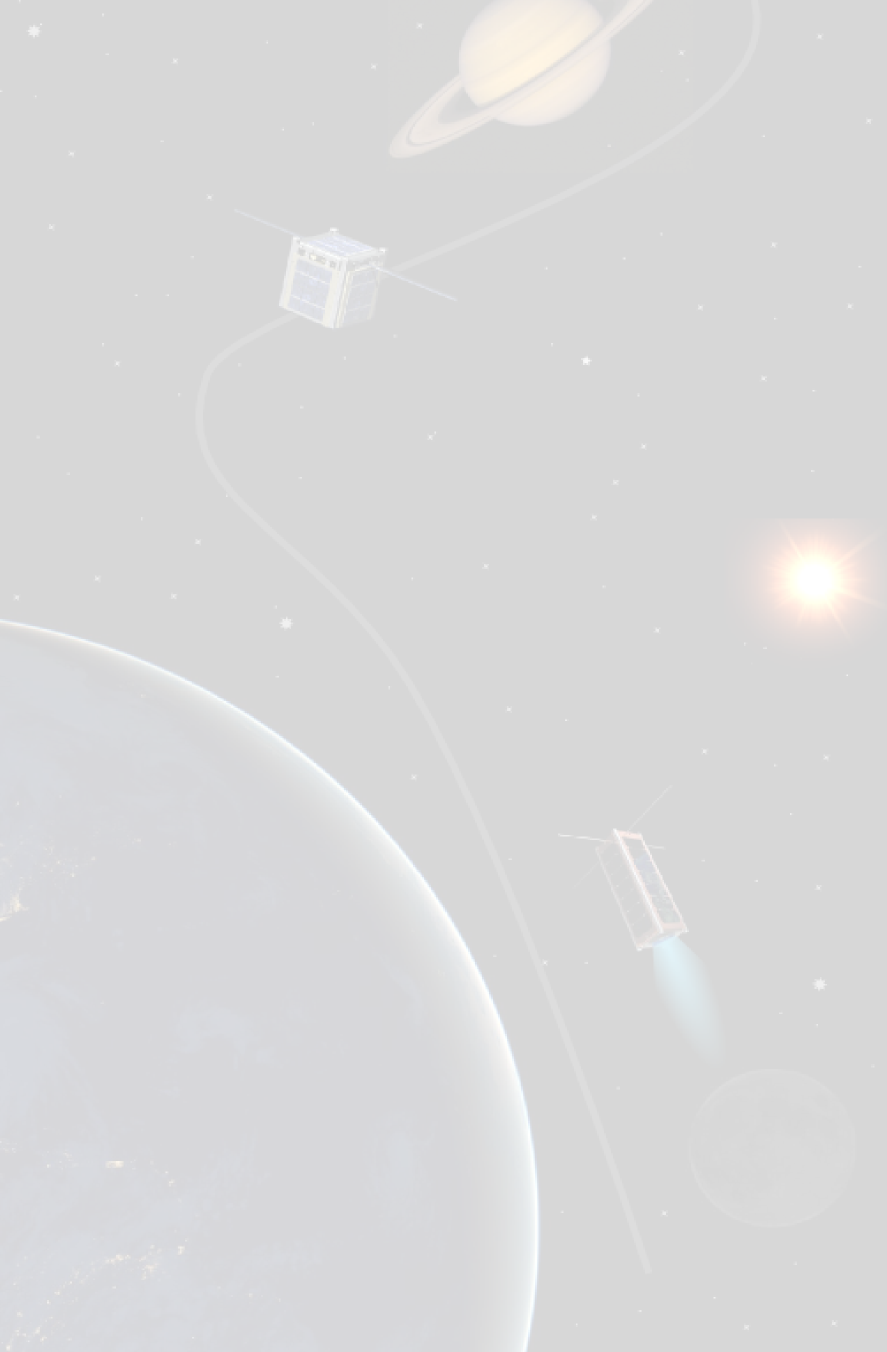

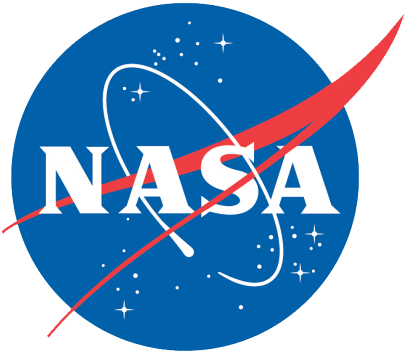

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