2018
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
May 7-8, 2018

www.intersmallsatconference.org

Monday, May 7, 2018

Time	**Event**
8:00-8:45	Registration
9:10-10:00	**Keynote Speaker: Charles Norton**
10:00-10:20	Coffee Break
10:20-11:35	**Session A: Interplantary SmallSat Missions** *Session chairs: K. Hogstrom and G. Elliott*
	A.1 EM1-Deployed Lunar Ice Cube Mission (*P. Clark*)
	A.2 BioSentinel – Lessons Learned During I&Test of the Spacecraft EDU (*R. Hanel*)
	A.3 Development of the LunaH-Map Mission (*C. Hardgrove*)
	A.4 Near Earth Asteroid Scout (*L. Johnson*)
	A.5 Lunar Flashlight (*J. Baker*)
11:35-12:00	**Session A Q&A Panel**
12:00-13:00	Lunch
13:00-14:45	**Session B: Mission Concepts and Instrumentation** *Session chairs: A. Marinan and E. Okoro*
	B.1 Flexibility, Validity and Susceptibility of Cylindrical Langmuir Probes for CubeSat and Pico-Satellite (*S. Bhattarai*)
	B.2 CubeSat Instrumentation Concept for Asteroid Exploration – The ASPECT Platform (*A. Näsilä*)
	B.3 Exploring Off-World Lava Tubes and Caves Using Small Robots (*H. Kalita*)
	B.4 Mars Aerosol Tracker (MAT): A SmallSat to Monitor Dust Storms and Water Ice Clouds (*L. Montabone*)
	B.5 Overview and Results from the ESA CDF Study on Small Planetary Platforms (*S. Bayon*)
	B.6 Heliophysics Interplanetary Small Satellite Missions and Enabling Optical Communication (*H. Spence*)
	B.7 CubeSub – A Submersible Concept for Underwater Planetary Exploration (*K. Inamdar*)
14:45-15:15	**Session B Q&A Panel**
15:15-15:45	Coffee Break

Monday, May 7, 2017 *(continued)*

Time	**Event**
15:45-17:30	**Session C: Propulsion, Trajectory, and Launch Support** *Session chairs: A. Austin and Y. Lee*
	C.1 IFM Nano Thruster: High Total Impulse Propulsion for Small Satellites (*D. Krejci*)
	C.2 An Orbital Maneuvering Vehicle for Transport Beyond Earth Orbit (*C. Loghry*)
	C.3 Trajectory Design for Asteroid Proximity Exploration (*R. Nallapu*)
	C.4 Interorbital Systems: Launch Services to LEO, Luna, and Beyond (*R. Milliron*)
	C.5 Modular Solar Steam Propulsion Units for Interplanetary Applications (*J. Dominguez*)
	C.6 Cubesatellite Replication of Deep Space Fuel Transfer (*N. Patel*)
	C.7 Essentially Free: Shipping from Asteroids, Moons and Planets to Earth (*D. Taylor*)
17:30-18:00	**Session C Q&A Panel**
18:00-20:00	Dinner and Social

Tuesday, May 8, 2017

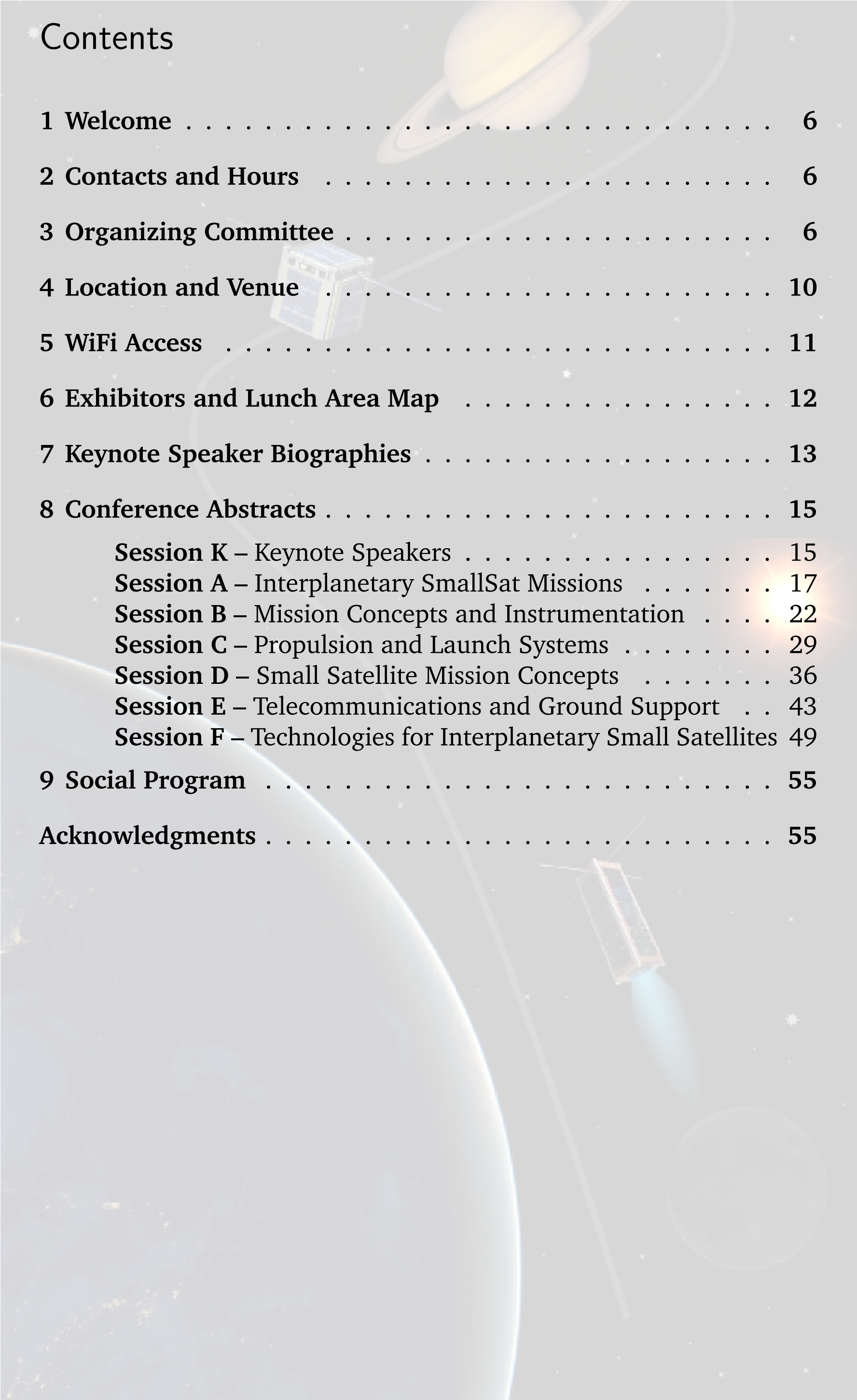
Time	**Event**
8:00-9:10	Registration
9:10-10:00	**Keynote Speaker: Sergio Pellegrino**
10:00-10:20	Coffee Break
10:20-12:05	**Session D: Small Satellite Mission Concepts** *Session chairs: P. Clark and R. Staehle*
	D.1 Cupid's Arrow – a Small Interplanetary Probe Concept (*A. Freeman*)
	D.2 Primitive Object Volatile Explorer (PrOVE) – Waypoints and Opportunistic Missions to Comets (*T. Hewagama*)
	D.3 PRISM: Phobos Regolith Ion Sampling Mission with Compact SIMS (*M. Collier*)

Tuesday, May 8, 2017 *(continued)*

	D.4 ZodiScout: A Small Satellite to Explore the Origins of the Interplanetary Dust in ou rSolar System (*V. Gorjian*)
	D.5 A Venus SmallSat Orbiter for Remote Sensing of Seismic Activity, the VAMOS Concept (*A. Didion*)
	D.6 MISEN: The Mars Ion and Sputtering Escape Network (*R. Lillis*)
	D.7 Deep Space 9 Mission concept – Secondary Payload Study for the proposed Next Mars Orbiter (*T. Schulter*)
12:05-12:30	**Session D Q&A Panel**
12:30-13:30	Lunch
13:30-15:00	**Session E: Telecommunications and Ground Support** *Session chairs: C. Lau and B. Malphrus*
	E.1 Progress Update on the Morehead State University Ground System for Interplanetary CubeSat Missions (*B. Malphrus*)
	E.2 Deployable Faceted Cassegrain Reflectarray Antenna for CubeSats (*A. Darnell*)
	E.3 DTN for Interplanetary SmallSat Missions (*N. Richard*)
	E.4 Advanced Multi-Mission Operations System Instrument Toolket: An Open-Source Instrument and Small Sat Ops Toolkit (*M. Joyce*)
	E.5 Structurally Reconfigurable Module Inflatable Reflectors (*A. Chandra*)
	E.6 Recent Developments in Small Satellite Antenna Technology (*R. Hodges*)
15:00:15:30	**Session E Q&A Panel**
15:30:16:00	Coffee Break

Tuesday, May 8, 2017 *(continued)*

16:00-17:30	**Session F: Autonomy, Pointing, and EDL** *Session chairs: C. Lee and J. Thanga*
	F.1 New Avenues for Planetary Science Using On-Orbit CubeSat Centrifuges (*E. Asphaug*)
	F.2 Autonomous Path Planning for Climbing in Low-Gravity Planetary Bodies (*S. Morad*)
	F.3 Guidance, Navigation and Control of SPIKE for Descent, Landing and Hopping on an Asteroid (*H. Kalita*)
	F.4 6U Deployable Solar Arrays for Deep Space Missions (*V. Diaz*)
	F.5 An Advanced Packaging Approach for a High-Performance Deployable Photovoltaic System R-HaWK (*E. Ruhl*)
	F.6 An In-Orbit Fuel Supply: Enabling SmallSats with Extreme Delta-V (*D. Faber*)
17:30:18:00	**Session F Q&A Panel**
18:00-18:05	Closing Remarks



Contents

1. Welcome

Welcome to the sixth 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 May 7 and from 8:00 am to 3:00 pm on May 8. Please don't hesitate to contact the organizing committee at info@intersmallsatconference.org at any time during the conference.

3. Organizing Committee

Alessandra Babuscia received her B.S. and M.S degrees from the Politecnico di Milano, Milan, Italy, in 2005 and 2007, respectively, and her Ph.D. degree from the Massachusetts Institute of Technology (MIT), Cambridge, in 2012. She is currently a Telecommunication Engineer at NASA JPL (337G). She has developed communication systems for different university missions (CASTOR, ExoplanetSat, TerSat, REXIS, TALARIS). She has been with the Communication Architecture Research Group, NASA Jet Propulsion Laboratory, Pasadena, CA. Her current research interests include communication architecture design, statistical risk estimation, multidisciplinary design optimization, and mission scheduling and planning. She was a member of the organizing committee for iCubeSat 2012 (MIT, Cambridge), and she is a session chair at the IEEE Aerospace Conference.

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.

Kristina Hogstrom received her B.S. in Mechanical Engineering with a minor in Astronomy from Boston University in 2011 and her M.S. and Ph.D. in Space Engineering from Caltech in 2012 and 2017 respectively. At Caltech, she was a NASA Space Technology Research Fellow and a Keck Institute for Space Studies Fellow. Her doctoral research focused on the behavior of deployable modules for robotically assembled space structures, such as large space-based optical reflectors. She is now a systems engineer at JPL in the mission formulation section and has an active role on Team X, a concurrent engineering team that rapidly explores, designs, and evaluates mission concepts in the early stages of development.

Alex Austin received a bachelor's degree in aeronautical and mechanical engineering and a master's degree in aeronautical engineering from Rensselaer Polytechnic Institute (RPI) in 2016. His research focused on the optimization of multicopter rotor designs using computational fluid dynamics. While at RPI, Alex also worked on a CubeSat project to design a system capable of capturing and deorbiting a small piece of space debris. He currently works as a Systems Engineer in the Advanced Design Engineering Group at NASA JPL, where he supports a number of early formulation projects and mission proposals. Alex also works closely with the JPL concurrent engineering design teams (A-Team, Team X, and Team Xc) to rapidly create and evaluate new mission concepts.

Chi-Wung Lau is a member of the Signal Processing Research group at Jet Propulsion Laboratories. He has been working at JPL for 15 years and has been involved with such projects as Galileo, Deep Impact, MER, Phoenix and MSL. Research areas of interest are 34 meter array tracking quantum communications, and link analysis. He received bachelors from U.C. Berkeley in 1996 and masters from the University of Southern California in 2001.

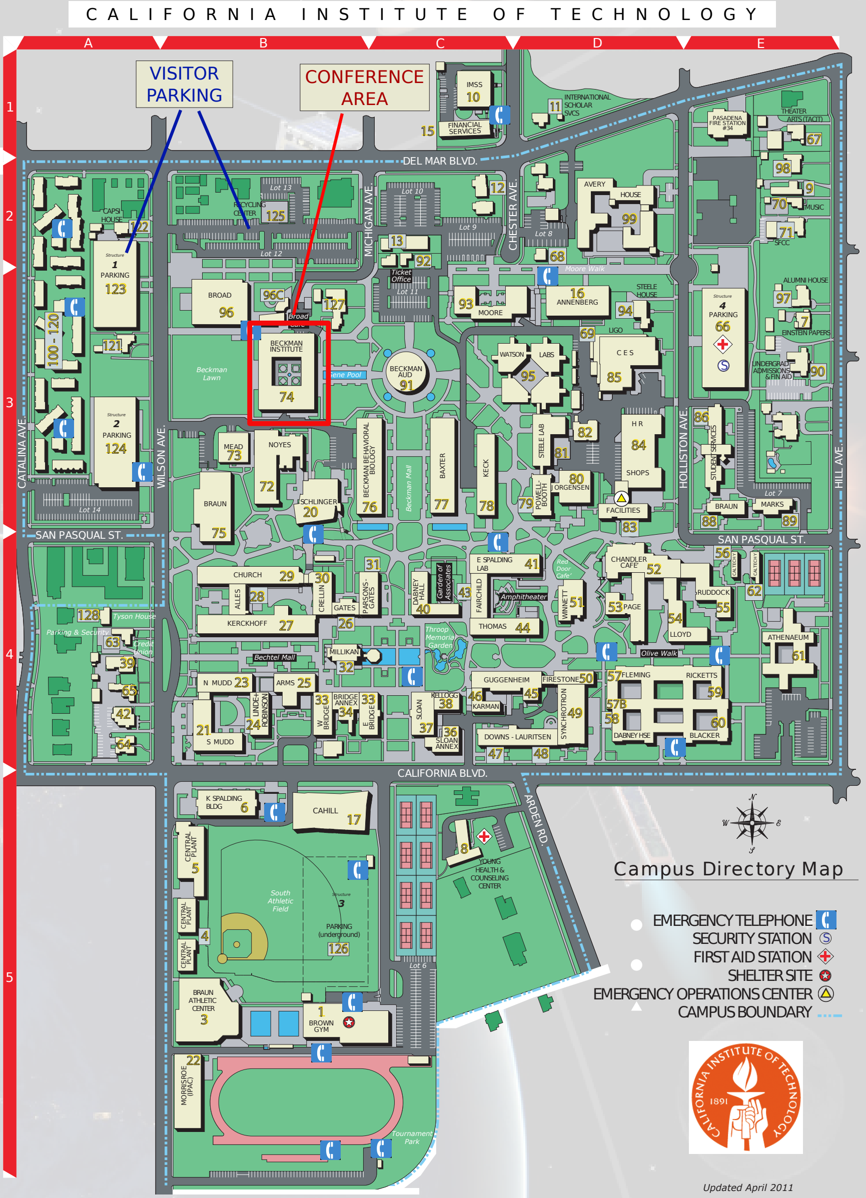
Pamela Clark, of the Advanced Instrument Concepts and Science Applications Group in the Instrument Division, at Jet Propulsion Laboratory, California Institute of Technology, is Technical Advisor of the JPL Cubesat Development Lab. She is also Science PI of the NASA EM1 Lunar IceCube Mission, as well as Convener and Program Chair for the Annual LunarCubes Workshops, and an adjunct research professor at Catholic University of America. She holds a PhD in Geochemical Remote Sensing from University of Maryland. Her interests include extending the cubesat paradigm to deep space technology demonstrations and science requirements driven cubesat missions, developing compact science instruments, evolving a low-cost development model for deep space missions, and using the cubesat paradigm to set up distributed networks for studying whole system dynamics. She is the author of several books, including Remote Sensing Tools for Exploration, Constant-Scale Natural Boundary Mapping to Reveal Global and Cosmic Processes, and Dynamic Planet: Mercury in the Context of its Environment.

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

Annie Marinan earned her Bachelor's degree from the University of Michigan in Aerospace Engineering in 2011 and her Master's and PhD in Aerospace Engineering (Space Systems) from the Massachusetts Institute of Technology (MIT) in 2013 and 2016, respectively. Her graduate research focused on use of CubeSats for atmospheric sounding and as technology demonstration platforms. She is currently working as a systems engineer at NASA's Jet Propulsion Laboratory (JPL) in the Project Systems Engineering and Formulation Section. She leads Team Xc, a concurrent engineering team that focuses on design and feasibility assessments for small spacecraft missions.

4. Location and Venue

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



CALIFORNIA INSTITUTE OF TECHNOLOGY

Buildings by Name

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
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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

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

Buildings by Number

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

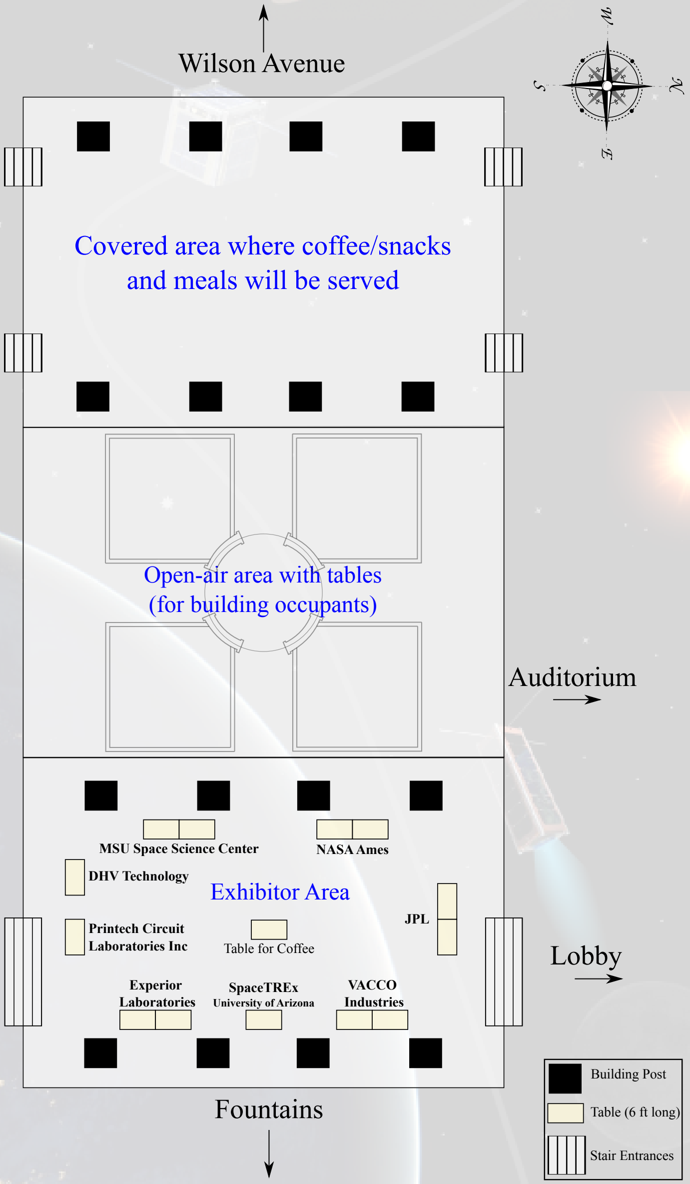
Updated April 2011

5. WiFi Access

For wireless internet access, connect to the “Caltech Conference” network. Login information is posted and available in the conference venue.

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. Keynote Speaker Biographies

Charles Norton (*NASA Headquarters*)

Dr. Charles D. Norton is currently the NASA SMD Assistant Deputy Associate Administrator for Small Spacecraft Programs responsible for establishing NASA's strategic direction for innovative small satellite science missions from ESPA-Class spacecraft down to CubeSats. Prior to this appointment, he served as a program area manager and principal technologist at the Jet Propulsion Laboratory, California Institute of Technology as the Advanced Information Systems Technology (AIST) and In-Space Validation of Earth Science Technologies (InVEST) Program Associate for NASA's Earth Science Technology Office (ESTO) at JPL. He has also served as the JPL engineering and science directorate formulation lead for Small Satellites with additional duties within various JPL strategic investment and formulation committees. His research interests include small satellite spaceborne technology validation, high-performance computing for Earth and space science modeling, and advanced information systems technologies. He has managed multiple CubeSat flight projects, co-led a Caltech Keck Institute for Space Sciences Study Program on "Small Satellites: A Revolution in Space Science", and co-authored two 2 National Academies of Science reports on "Achieving Science with CubeSats: Thinking Inside the Box" and "Powering Science: NASA's Large Strategic Science Missions". Prior to joining JPL, he was a National Research Council Postdoctoral Fellow. He has given more than 30 national and international keynote/invited talks; published in various journals, conference proceedings, and book chapters, and is a recipient of numerous awards for new technology and innovation, including the JPL Lew Allen Award and the NASA Exceptional Service Medal.

Sergio Pellegrino

(*Caltech*)

Sergio Pellegrino, Joyce and Kent Kresa Professor of Aeronautics and Professor of Civil Engineering at the California Institute of Technology and JPL Senior Research Scientist, received a Laurea in Civil Engineering from the University of Naples in 1982 and a PhD in Structural Mechanics from the University of Cambridge in 1986.

His general area of research is the mechanics of lightweight structures, with a focus on packaging, deployment, shape control and stability. With his students and collaborators, he is currently working on novel concepts for future space telescopes, spacecraft antennas, and space-based solar power systems.

As a member of the NASA Superpressure Balloon design team, for over 10 years he has worked on analysis methods for stratospheric balloons. Dr Pellegrino's publications have been selected for several awards, including the ICE James Watt Medal 2000; AIAA Gossamer Spacecraft Forum Best Paper Award in 2004, 2005, 2006, 2011 and 2013; IASS Tsuboi Award in 2004, 2005, and 2007; ASME/Boeing Best Paper Award in 2008; and ASME Mechanisms and Robotics Committee Best Paper Award in 2013. He has received a Pioneers' Award in 2002 from the Space Structures Research Center, University of Surrey and a NASA Robert H. Goddard Exceptional Achievement Team Award in 2009.

Dr Pellegrino is a Fellow of the Royal Academy of Engineering, a Fellow of AIAA and a Chartered Structural Engineer. He is President of the International Association for Shell and Spatial Structures (IASS) and Editor-in-Chief of the Journal of the IASS. Dr Pellegrino is the author of over 250 technical publications.

8. Conference Abstracts

K.1 NASA's Strategic Goals for Small Satellite Science

Charles Norton
(*NASA Science Mission Directorate*)

NASA's Science Mission Directorate (SMD), in collaboration with other organizations in the agency, is aggressively pursuing how small spacecraft can contribute to a balanced portfolio of strategic high priority science missions. The agency has over 40 CubeSat and SmallSat spacecraft and constellation missions in development, or completed to date, that have advanced new remote sensing technologies and explored how science can be achieved from these platforms. This talk will review what has been accomplished thus far and describe specific actions and future planned initiatives NASA SMD is pursuing to enable small spacecraft missions to contribute to NASA's overall strategic science objectives.

K.2 Technology Demonstration of Self-Assembling Space Telescopes Using Nanosatellites

Sergio Pellegrino
(*JPL/Caltech*)

In-space assembly of large telescopes requires new technologies for autonomous maneuvers and docking, active mirrors, metrology, etc. Inspired by a study of large space apertures at the Keck Institute of Space Studies, a team formed by students at Caltech, the University of Surrey (UK), and the Indian Institute of Space Science and Technology (India), is developing the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) technology demonstration. The mission will involve two "3U" class nanosatellites ("MirrorSats") each carrying an electrically actuated adaptive mirror, and each capable of autonomous un-docking and re-docking with a small central "9U" class nanosatellite ("CoreSat"), which houses two fixed mirrors and a boom-deployed focal plane assembly. All three spacecraft will be launched as a single 30 kg microsatellite package. This educational project started in 2010 and is currently at the flight integration/testing stage. It has provided an opportunity for over 120 Caltech undergraduates and graduate students to work on their own flight mission. More details can be found at: pellegrino.caltech.edu/aarest1

A.1 EM1-deployed Lunar Ice Cube Mission

Pamela Clark (*JPL/Caltech*),
Ben Malphrus (*Morehead State University*),
Cliff Brambora, David Folta (*NASA GSFC*), Michael Tsay (*Busek*),
Lauren McNally (*JPL/Caltech*)

Overview: Lunar Ice Cube will be deployed in cis-lunar space in 2019 by NASA's EM1 mission. Lunar Ice Cube was selected by the NASA HEOMD NextSTEP program to demonstrate cubesat propulsion (Busek BIT 3 RF Ion engine), and a cubesat-scale instrument capable of addressing Strategic Knowledge Gaps related to lunar volatile distribution (abundance, location, and transportation physics of water ice). We will also demonstrate for the first time in deep space an inexpensive radiation-tolerant flight computer (Space Micro Proton 400K), the GSFC Core Flight Executive Operating System, a custom pumpkin power system, and AIM/IRIS microcryocooler.

Payload: The payload consists of one instrument: BIRCHES [1], Broadband IR Compact High-resolution Exploration Spectrometer. The versatile instrument, being developed by NASA GSFC, is designed to provide the basis for amplifying our under-standing [2,3,4] of the forms and sources of lunar volatiles in spectral, temporal, spatial, and geological context as function of time of day and latitude. BIRCHES is a compact version (1.6 U, 3 kg, 10-20 W) of OVIRS on OSIRIS-REx [5], a point spectrometer with a cryocooled HgCdTe focal plane array for broadband (1 to 4 micron) measurements. The instrument will achieve sufficient SNR ($>$200) and spectral resolution ($\leq$ 10 nm @ 3 microns) through the use of a Linear Variable Filter to characterize and distinguish spectral features associated with water. An adjustable field stop allows as to change the footprint dimensions by an order of magnitude, to adjust for variations in altitude and/or incoming signal. The compact and efficient AIM microcryocooler/IRIS controller is designed to maintain the detector temperature below 115K.

Mission Design: Science data-taking with the BIRCHES payload will occur primarily during the science orbit (100 km x 5000 km, equatorial periapsis, nearly polar), highly elliptical, with a repeating coverage pattern that provides overlapping coverage at different lunations. Particular attention will be paid to systematic or solar activity dependent transient effects resulting from charged particle interactions around the terminators. Science orbit data-taking will last approximately 6 months, 6 lunar cycles, allowing for sufficient collection of systematic measurements as a function of time of day to allow derivation of volatile cycle models.

References:

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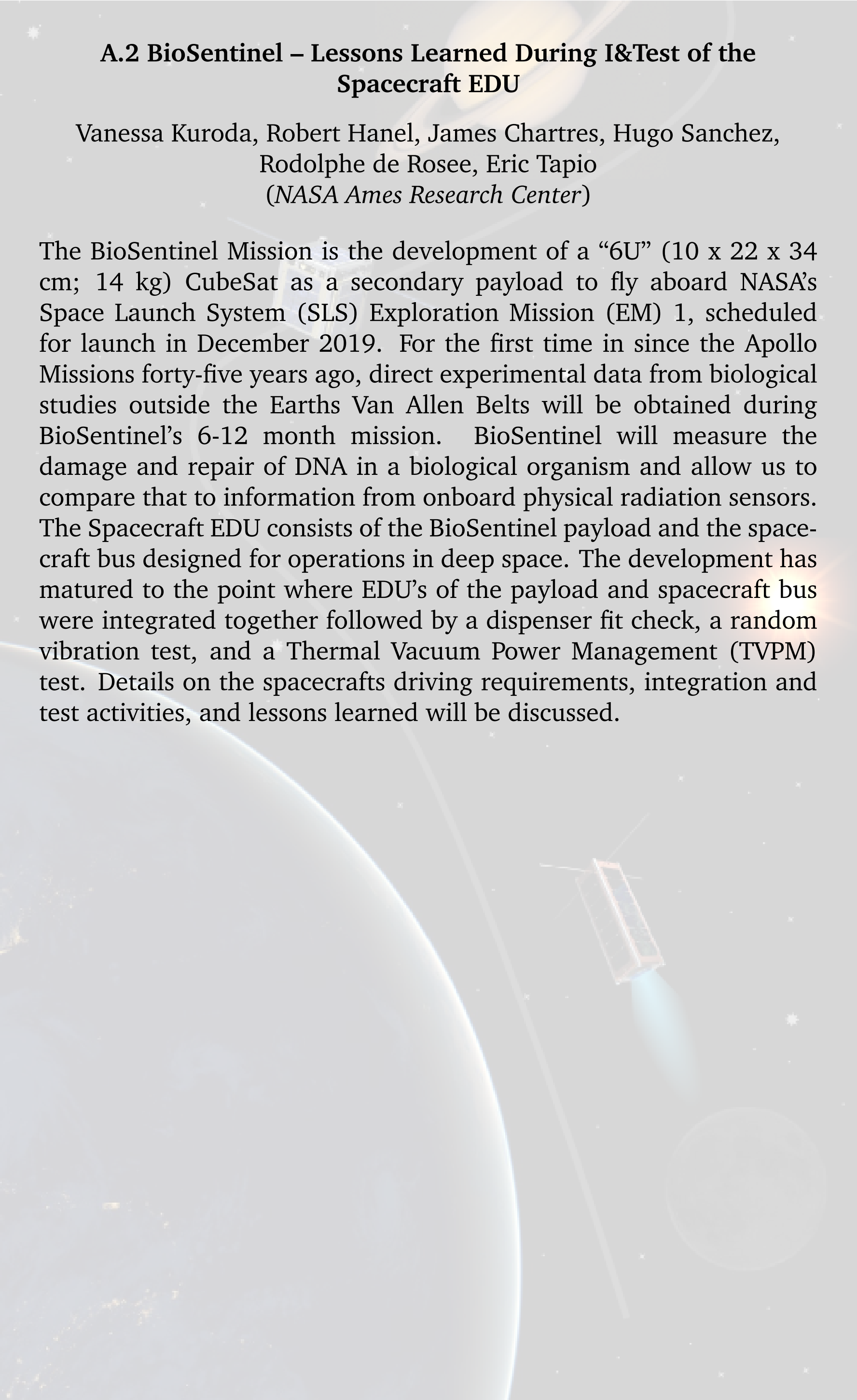
[5] Reuter, D. and A. Simon-Miller, (2012) Lunar and Planetary Science, 1074

A.2 BioSentinel – Lessons Learned During I&Test of the Spacecraft EDU

Vanessa Kuroda, Robert Hanel, James Chartres, Hugo Sanchez,
Rodolphe de Rosee, Eric Tapio
(*NASA Ames Research Center*)

The BioSentinel Mission is the development of a “6U” (10 x 22 x 34 cm; 14 kg) CubeSat as a secondary payload to fly aboard NASA’s Space Launch System (SLS) Exploration Mission (EM) 1, scheduled for launch in December 2019. For the first time in since the Apollo Missions forty-five years ago, direct experimental data from biological studies outside the Earths Van Allen Belts will be obtained during BioSentinel’s 6-12 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. The Spacecraft EDU consists of the BioSentinel payload and the spacecraft bus designed for operations in deep space. The development has matured to the point where EDU’s of the payload and spacecraft bus were integrated together followed by a dispenser fit check, a random vibration test, and a Thermal Vacuum Power Management (TVPM) test. Details on the spacecrafts driving requirements, integration and test activities, and lessons learned will be discussed.



A.3 Development of the LunaH-Map Mission

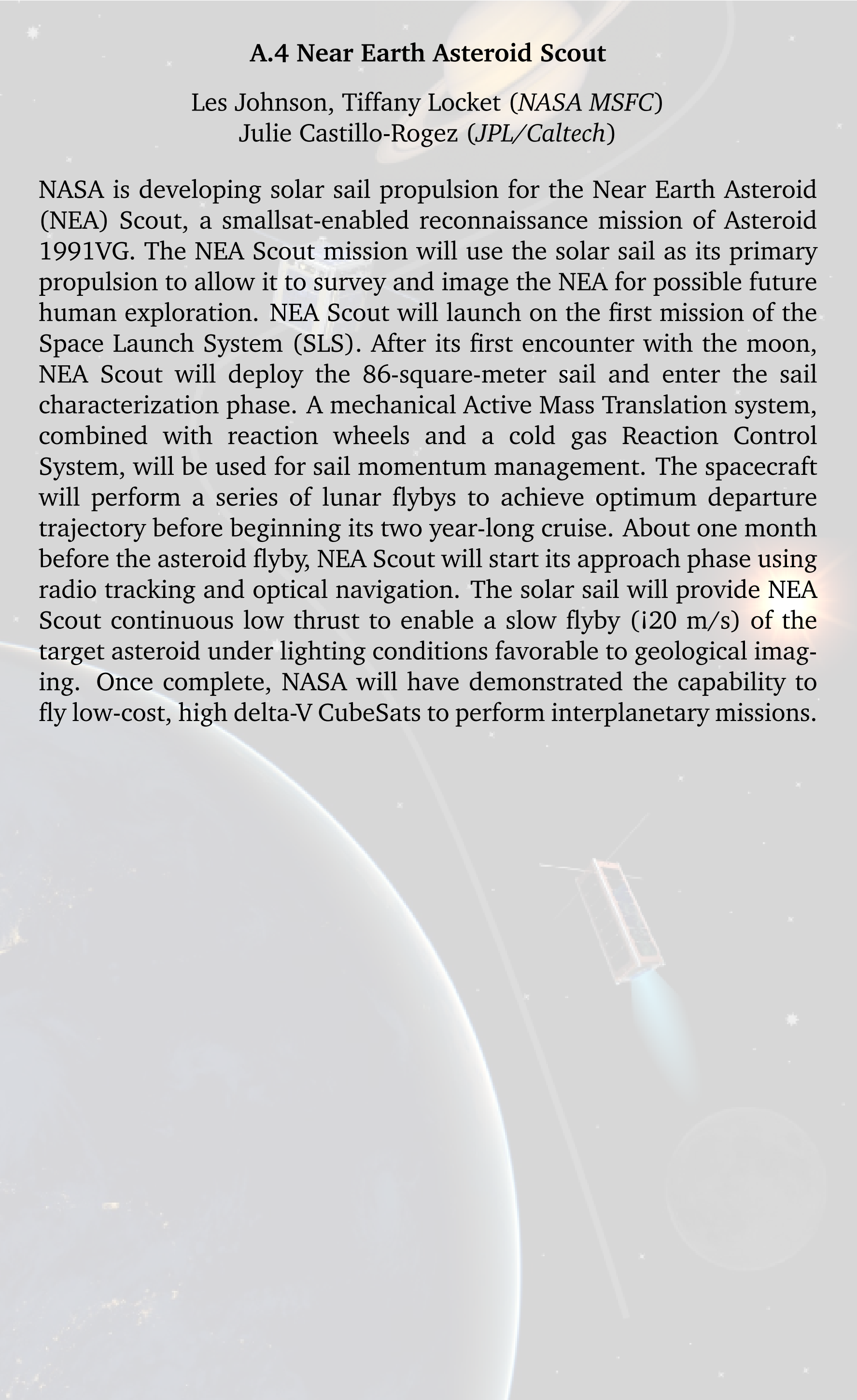
Craig Hardgrove
(*Arizona State University*)
J. Bell, R. Starr, A. Colaprete, D. Drake, I. Lazbin, S. West, E. Johnson, James Christian, L. Heffern, A. Genova, D. Dunham, B. Williams, D. Nelson, S. Puckett, N. Struebel, A. Babuscia, P. Scowen, H. Kerner, R.J. Amzler

The Lunar Polar Hydrogen Mapper (LunaH-Map) is a 6U CubeSat selected for flight on the Space Launch System (SLS) Exploration Mission 1 (EM-1) through NASA's Science Mission Directorate under the Small, Innovative Missions for Planetary Exploration (SIMPLEx) program. Results from previous scientific missions to the Moon have identified the presence of water/frost within permanently shadowed regions (PSRs) at the poles, however, there remains uncertainty about the bulk (non-surficial/frost) abundance of these enrichments and whether these small-scale enrichments are pervasive throughout lunar south pole PSRs. Placing constraints on the bulk hydrogen abundance within PSRs will help point to specific processes and delivery sources for polar volatiles, and can help resolve mechanisms operating over long time scales (e.g. solar wind) from other, much shorter time scale delivery mechanisms (e.g. passing asteroids or comets). Hydrogen enrichments between 500 to 600 ppm at a spatial scale of 5-15 km could provide robust evidence for discerning hypotheses regarding transport processes of polar hydrogen enrichments. The LunaH-Map spacecraft is equipped with gimbaled solar arrays, 3 reaction wheels, a star tracker, an X-Band radio, a command and data handling system, power control system, neutron spectrometer array, and a low-thrust propulsion system. The current mission science phase achieves 282 orbits over two lunar days and preliminary analysis of the miniature neutron spectrometer (Mini-NS) sensitivities shows the mission will be capable of identifying small-scale (<15 km^2) regions of hydrogen enrichments on the order of 600ppm $\pm$ 120ppm. Communication with Earth will be achieved via the Iris radio, to be used on the MarCO spacecraft at Mars, and will be coordinated with the Deep Space Network. Spacecraft operations, telemetry and science data analysis will be conducted at the Mission Operations Center at Arizona State University (ASU). After deployment from SLS EM-1, LunaH-Map will maneuver and perform a lunar flyby targeting the Earth-Moon L2 point and eventual capture by the Moon within two months. Upon lunar capture the spacecraft will spiral down to an elliptical low-altitude science orbit with perilune at the South Pole. During the science phase, the Mini-NS will measure neutron counts about the perilune (lowest altitude passes) of each orbit to enable mapping of hydrogen enrichments within PSRs. The mean perilune altitude is designed to achieve between 10 to 15 km above terrain poleward of 85°S throughout the science phase, but will vary depending upon the final SLS EM-1 launch date and trajectory.

A.4 Near Earth Asteroid Scout

Les Johnson, Tiffany Locket (*NASA MSFC*)
Julie Castillo-Rogez (*JPL/Caltech*)

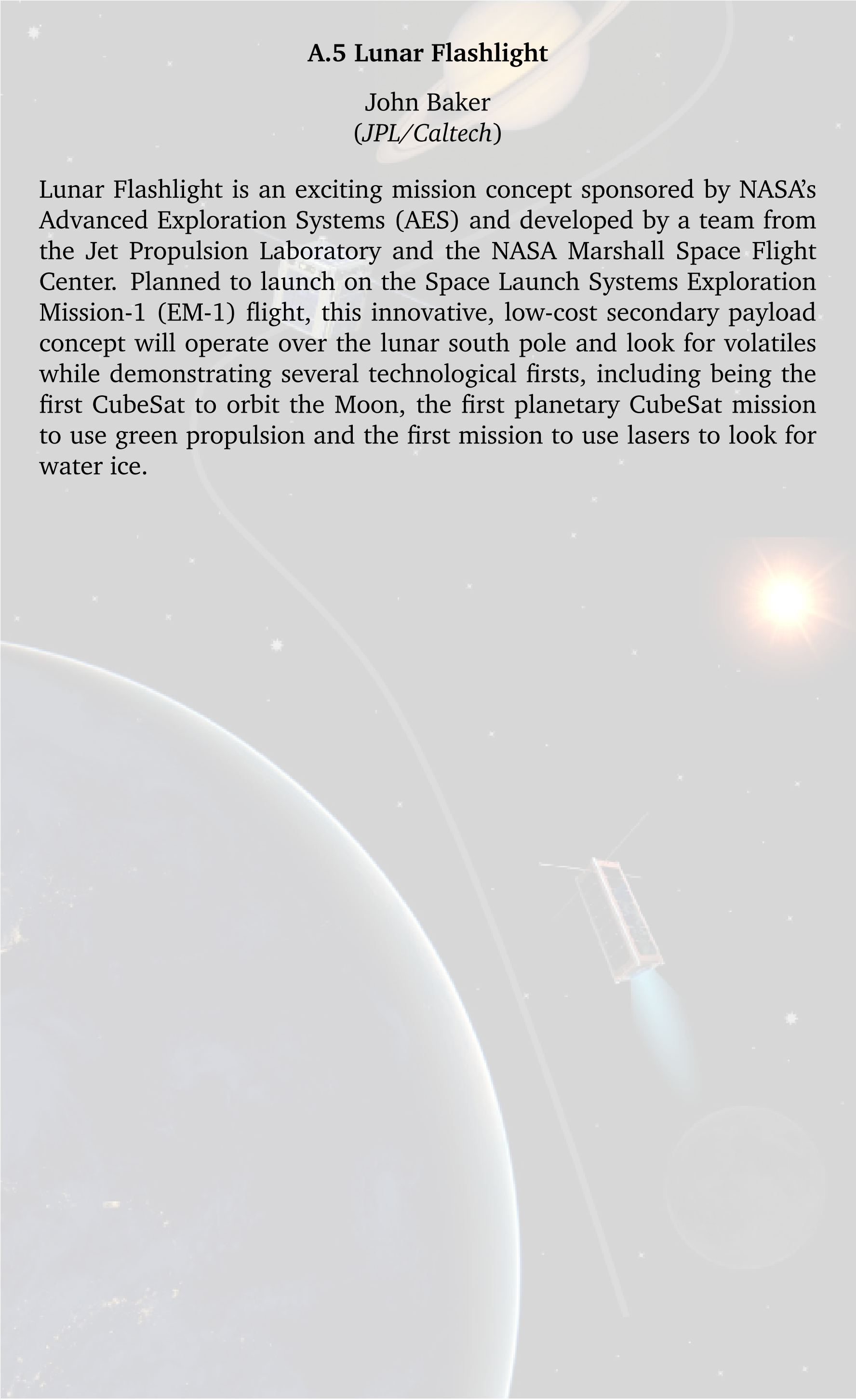
NASA is developing solar sail propulsion for the Near Earth Asteroid (NEA) Scout, a smallsat-enabled reconnaissance mission of Asteroid 1991VG. The NEA Scout mission will use the solar sail as its primary propulsion to allow it to survey and image the NEA for possible future human exploration. NEA Scout will launch on the first mission of the Space Launch System (SLS). After its first encounter with the moon, NEA Scout will deploy the 86-square-meter sail and enter the sail characterization phase. A mechanical Active Mass Translation system, combined with reaction wheels and a cold gas Reaction Control System, will be used for sail momentum management. The spacecraft will perform a series of lunar flybys to achieve optimum departure trajectory before beginning its two year-long cruise. About one month before the asteroid flyby, NEA Scout will start its approach phase using radio tracking and optical navigation. The solar sail will provide NEA Scout continuous low thrust to enable a slow flyby (¡20 m/s) of the target asteroid under lighting conditions favorable to geological imaging. Once complete, NASA will have demonstrated the capability to fly low-cost, high delta-V CubeSats to perform interplanetary missions.



A.5 Lunar Flashlight

John Baker
(*JPL/Caltech*)

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



B.1 Flexibility, Validity and Susceptibility of Cylindrical Langmuir Probes for CubeSat and Pico-Satellite to Characterize Ionosphere and Thermosphere Plasma

Shankar Bhattarai
(*Tribhuvan University*)

Nobel Laureate Irving Langmuir pioneered the use of electrostatic probes to measure the electron temperature, number density, floating potential, and plasma potential in ionized gases (in the 1920's). Langmuir probe is comprised of an exposed conductor (e.g., wire) immersed within a plasma. The theory of interpreting the data acquired (namely the current drawn from the plasma at a sequence of different bias voltages) from Langmuir probes is well established. Druyvesteyn noted that the second derivative of the probe current with respect to the bias voltage is proportional to the electron energy distribution function. The analysis by Laframboise enabled accurate evaluation of experimental data for cylindrical and spherical probes regardless of sheath size. PEPL makes extensive use of planar and cylindrical Langmuir (single, double, and triple) probes for evaluating plasma properties in the plumes of thrusters and in near electrode regions. The small size of typical Langmuir probes coupled with their relatively simple theory of operation make them an indispensable and widely used plasma diagnostic. We can constructs custom probes sized to each experiment, commercially available systems do exist. This research paper explore the reliability, validity and susceptibility of small dimensional Langmuir Probe in CubeSat and Pico-Satellite for Ionosphere Characterizations. There is no general theory of Langmuir probes which is applicable to all measurement conditions, because it depends on the probe size and geometry, plasma density and temperature, platform velocity, and other factors. The actual design of the probe is usually determined by considering the relationship between the probe dimensions and the Debye length of the plasma.

B.2 Cubesat Instrumentation Concept for Asteroid Exploration – The ASPECT Platform

Antti Näsilä (*VTT Technical Research Centre of Finland Ltd*),
Tomas Kohout (*University of Helsinki*),
Roberts Trops, Kai Viherkanto, Heikki Saari, Anna Rissanen
(*VTT Technical Research Centre of Finland Ltd*)

The ASPECT platform aims to study the composition of planetary bodies and the effects of space weathering in order to gain understanding of the formation and evolution of the Solar System. Originally the concept was created as a part of the ESA/NASA AIDA (Asteroid Impact & Deflection Assessment) Mission, but it has since evolved to a generic nanosatellite mission concept suitable for any deep space exploration mission.

ASPECT is a CubeSat equipped with a spectral imager which measures from 0.5 um up to 2.5 μm. This wavelength range allows the mapping of surface composition with good accuracy. As the instrument is a spectral imager, it will also provide spatial information about the target, which helps in determining the composition differences over the planetary body. Knowledge of asteroid composition, the physical appearance of asteroids, and the correct interpretation of their reflectance spectra, are issues of key importance in planetary science.

In recent years, VTT has developed several hyperspectral imager payloads for small satellite missions based on tunable piezo-actuated FPI filters, which can be realized for various different wavelengths from ultraviolet to thermal infrared to enable different application needs. Instrument size is typically very small (0.5U) and light-weight ($<$ 600 g). 2D snapshot hyperspectral imagers are especially suitable for nanosatellite missions, as the whole 2D scene is imaged at once and the spectral data cube is constructed by taking multiple images of the same target at different wavelengths. This makes the instrument very robust and also software programmable - same spectral sensing hardware can adapt to different application needs through programming of the wavelength selection even after launch.

VTT has previously realized three payloads: The first visible - VNIR demonstrator for imaging between 500 nm and 900 nm has been launched on-board the Aalto-1 nanosatellite. The 2nd Vis-VNIR instrument will measure stratospheric ozone by solar occultation by recording the atmospheric transmission between 430 nm and 800 nm at different altitudes on board the PICASSO nanosatellite, aiming for launch in 2018. The latest payload is the first CubeSat-compatible miniaturized SWIR hyperspectral imager for the wavelengths between 925 $-$ 1400 nm (1000 $-$ 1600 nm) to be launched to space in 2018 Reaktor Hello World CubeSat mission. The ASPECT spectral imager concept is realized by combining the previously developed instruments to a single instrument while adding an extra single-point spectrometer to cover the wavelength range from 1.6 μm to 2.5 μm.

B.3 Exploring Off-World Lava Tubes and Caves Using Small Robots

Himangshu Kalita, Steven Morad, Jekan Thangavelautham
(*University of Arizona/SpaceTREx*)

Detailed surface images of the Moon and Mars from Lunar Reconnaissance Orbiter Camera and HiRise camera respectively reveal hundreds of cave-like openings. These cave-like openings have been theorized by planetary scientists like Dr. Mark Robinson and his team to be remnants of lava-tubes and their interior maybe in pristine conditions and maybe ideally suited for These locations may have well preserved geological records of the Moon and Mars, including evidence of past water flow, habitability and major geological events. Exploration of these caves using wheeled rovers remains a daunting challenge. These caves are likely to have entrances with caved-in ceilings much like the lava-tubes of Arizona and New Mexico. Thus, the entrances are nearly impossible to traverse even for experienced human hikers. Our approach has been to take advancement from CubeSat and small satellite technology and apply them to flying robots that would explore these lava tubes. We have introduced the SphereX robot, a 3 kg, 30 cm diameter robot with computer hardware and sensors of a smartphone attached to rocket thrusters. Each SphereX robot can hop, roll or fly short distances in low gravity, airless or low-pressure environments. Several SphereX robots maybe deployed to minimize single-point failure and exploit cooperative behaviors to traverse the cave. Our latest efforts are focused on showing an end to end mission concept to feasibly explore the far reaches of a cave network. For a minimal science mission, these robots need to obtain camera images and basic maps of the cave interior to be transmitted back to a lander or rover situated outside the cave. The teams of SphereX robots form a bucket brigade and partition the currently accessible volume of the cave. Then the teams of robots attempt to expand their reach deeper into the cave and sense their progress. Imaging the cave interior is expensive and require use of high-power strobe lights. The images would be compiled into a 3D point cloud and meshed by the lander or transmitted to ground. Using this conservative approach, we ensure the robots are always within communication reach of a lander/rover outside the cave. Once large segments of the cave are mapped, the rovers may lay down a network of mirrors to beam sunlight and laser light from a base station at the cave entrance to the far reaches of the cave. These mirrors also help the robots identify a pathway back to the cave entrance. Efforts are underway to perform field experiments to validate the feasibility our proposed approach to cave exploration.

B.4 Mars Aerosol Tracker (MAT): An Areostationary SmallSat to Monitor Dust Storms and Water Ice Clouds

Luca Montabone (*Space Science Institute*),
Michael VanWoerkom (*ExoTerra Resource LLC*),
Bruce Cantor (*Malin Space Science Institute*),
Michael J. Wolff (*Space Science Institute*),
Michael D. Smith (*NASA Goddard Space Flight Center*),
Francois Forget (*Laboratoire de Météorologie Dynamique*)

We have elaborated a mission concept to put a SmallSat (up to about 60 kg of mass) in an areostationary orbit around Mars – 17,031.5 km altitude above the equator. The planned areostationary orbit would be the first of its kind, offering the unequaled possibility to obtain a novel set of frequent observations over a region of the planet that can extend up to 80 away from the sub-spacecraft point.

The overall goal of this mission concept is to track Martian dust storms and water ice clouds, helping to address the scientific questions: What are the processes controlling the dynamics of dust and water ice aerosols, and promoting the evolution of regional dust storms into planetary-encircling storms?

The SmallSat uses a solar electric propulsion system based on micro Hall-effect thrusters that allow it to reach, optimize and maintain its orbit, dramatically improving its lifetime and control. The propellant is gaseous xenon. The power source is guaranteed by deployable, flexible, high specific power (160 W/kg) solar arrays designed to meet the power needs of the Hall-effect thruster and payload. Communication is provided in the X-band by the JPL IRIS Deep Space transponder in association with a KaPDA antenna.

The payload is comprised of one off-the-shelf visible camera (fixed-focus, narrow-angle lens, 5 MP resolution), and two thermal infrared cameras (fixed-focus, narrow-angle lens, 0.3 MP resolution). The infrared cameras are equipped with filter wheels for selecting multiple spectral ranges, and the uncooled micro-bolometer image sensors are responsive out to 20 μm to include CO_2, dust, and water ice absorption lines. Retrievals of aerosol optical depth throughout the local times will provide quantitative observations at a spatial resolution up to 60 km/pixel and temporal resolution up to half an hour, complementing the high-resolution daylight visible images (resolution up to 4 km/pixel).

We have studied three possible mission scenarios: 1) Ridesharing on a primary orbiter mission directed to Mars, with deployment after the initial capture burn (operated by the mothership). This scenario, which limits the use of thrusters, allows for the lowest mass and size; 2) Ridesharing on a primary mission directed to Mars with deployment a few weeks ahead of Mars capture (operated independently from the mothership); 3) An independent journey to Mars all the way from Earth GTO.

In all three cases, the duration of the (primary) science mission at Mars is planned for one Martian year.

B.5 OVERVIEW AND RESULTS FROM THE ESA CDF STUDY ON SMALL PLANETARY PLATFORMS

Silvia Bayon, Thomas Voirin
(*European Space Agency*)

Following a Call for “New Science Ideas”, the Science Future Missions Department of the European Space Agency (ESA) is taking some steps to investigate the use of small satellites for deep space planetary mission applications. The first of those steps has been to, after iteration with representatives from the European and Japanese planetary scientific communities, select three reference mission scenarios to run a short internal study at ESA’S Concurrent Design Facility (CDF). Two of the selected scenarios revolve around the idea of performing multi-point, simultaneous observations around a small body, either an active one in the Main Asteroid Belt or a non-active NEO. The third concept studied the application of small satellites for a multi-target mission to the Main Belt. These reference architectures do not correspond to real or candidate missions but were chosen for defining typical/envelope needs and to better understand the areas where technology developments are needed before the small satellites can be considered for implementation within the ESA Science Programme. This paper will outline the studied concepts and summarise the major outcomes and findings of the ESA CDF study on Small Planetary Platforms (SPP).

B.6 Heliophysics Interplanetary Small Satellite Missions and Enabling Optical Communication

Harlan E. Spence, Sonya Smith
(*University of New Hampshire*)

We discuss several heliophysics mission concepts that require interplanetary small satellites. One mission, called Interplanetary Neutron and Solar Particle Event CubesaT (INSPECT), follows an EM-1 orbital trajectory through interplanetary space with a 6U CubeSat. INSPECT explores solar neutrons and solar particle events as it moves inward from 1 AU toward Venus orbit; an EM-1-type launch provides an orbital trajectory that moves INSPECT approximately along the typical spiral of interplanetary magnetic fields (IMF). When combined with the large array of spacecraft near Earth that also measure solar particles, INSPECT will for the first time provide a dedicated set of measurements that quantify how the inner solar system connects magnetically with the Earth environment. This unique configuration allows INSPECT to answer two driving science questions from the most recent Solar and Space Physics Decadal Survey, namely: (1) determining how energetic particles accelerated by magnetic energy released explosively near the Sun propagate through the heliosphere; and, (2) developing advanced methods for forecasting and nowcasting of solar eruptive events and space weather through multipoint measurements of solar energetic particle radial and longitudinal distributions to clarify current environmental-model uncertainties. A second mission concept employs a small mothership with a swarm of CubeSats to resolve and quantify magnetized plasma turbulence in interplanetary space, simultaneously resolving both the ion and electron key size and time scales. Both missions benefit from the technology of deep space optical communication which, though considered a risk to missions of this sort in the past, has recent flight experience that would enable these and other interplanetary missions.

B.7 CubeSub – A Submersible Concept For Underwater Planetary Exploration

Karishma Inamdar (*International Space University, France*)
Hyuntae Kim (*ASRI, Seoul National University*)

Many of the underwater environments on Earth remain difficult to explore, due to their harsh environmental conditions and being hard to reach. The exploration of these places and the methodologies used could prove important first steps towards the exploration of the purported ocean worlds of our solar system such as Europa, Enceladus, Ceres, and perhaps even Charon.

This paper introduces the CubeSub concept and presents the first steps of its development. The CubeSub is a modular submersible based on subsystems and components originally designed for the CubeSat form factor. The CubeSubs main objective is to provide a submersible test bed for technology development and investigation of remote operational procedures in analog environments. It aims to be cheap, readily available and easy to use. The already well-established CubeSat framework offers a foundation for the CubeSub to build upon, and offers a substantial amount of already existing technology and industry competence; with its modular design it can easily be modified and augmented to suit the different needs of the users for a given mission.

The CubeSub was developed by a team of interns at NASA Ames Research Center, using rapid prototyping technologies such as 3D-printing and laser cutting, and uses commercial off-the-shelf components such as Arduino microcontrollers and sensors. The submersible's main functions are to gather information about water's properties, such as temperature, pressure, and depth, as well as to take pictures and videos from underneath the water and send it back to a surface device/computer. The prototype also demonstrated viability of inter-module wireless communication. The CubeSub team at Ames trying to combine the CubeSats and small submersibles and bringing that into a new area of underwater planetary exploration. CubeSats are based on miniaturization of electronics to explore low cost platforms. The CubeSub concept will allow us to explore areas that would otherwise be too costly or risky to access

C.1 IFM Nano Thruster: High total impulse propulsion for Small- and Nanosatellites enabling interplanetary missions

David Krejci, Alexander Reissner
(*ENPULSION*)
Bernhard Seifert
(*FOTEC*)

High specific impulse electric propulsion systems are capable of providing the necessary high total impulse required for actively propelled interplanetary missions even at compact scales required for small and Nanosatellites. Field-Emission Electric Propulsion (FEEP) thrusters are among the technologies capable of providing high specific impulses close to 10000s. The electrostatic acceleration of ions used in this principle makes FEEP thrusters highly efficient in terms of propellant usage, while the high density of the metal propellant yields high volumetric impulse, enabling uniquely small tank sizes per achieved delta v. The ENPULSION/FOTEC IFM Nano Thruster is a flight ready FEEP propulsion module, that has undergone a first in-orbit test on a Cubesat, which was recently launched in Jan 2018. The thruster is based on technology with exhaustive flight heritage, developed and qualified for agency sponsored science programs, and has been designed to fit into 0.8U envelope, with a maximum power requirement of 40W. The IFM Nano Thruster uses a metal propellant and is entirely inert during launch, without any moving parts or pressurized propellants. The standard-sized module can provide $>$5000-10000 Ns of impulse, resulting in $>$2km/s Δv for a 3kg Cubesat, allowing a variety of different maneuvers, including significant orbit change. During operation, the thruster can be throttled in terms of thrust, and can be varied in specific impulse from 2000s $-$ 6000s, depending on mission needs and available power. The thruster is modular in design, allowing clustering of thrusters to adapt to different mission needs.

C.2 An Orbital Maneuvering Vehicle for Transport Beyond Earth Orbit – Updated with the Morehead State University 21 m Ground Station

Christopher Loghry (*Moog Inc*)

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 vehicles structure low-cost space access can be provided through rideshare including the ability to multi-manifest payloads.

Moog presented a concept for a specific Earth/Sun L1 science mission in 2016 but since then has found many more use cases for a wide variety of missions. Moog has expanded its Orbital Maneuvering Vehicle (OMV) family to include even greater delta-V capabilities leverage bipropellant and electric propulsion systems that can be used to bring payloads such as Lagrange Points, Lunar Orbit, to the Asteroid Belt, and to Mars and beyond. The OMV can be more than a tug but part of the mission architecture including a communications relay or other “mothership” type applications. Using excess capacity on regular commercial GTO launches or even Space Launch System (SLS) 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. Herein is a summary of these assessments and mission designs over the last two years including providing summaries for efforts done jointly with NASA Glenn, Marshall, Goddard, and JPL.

C.3 Trajectory Design for Asteroid Proximity Exploration

Ravi Teja Nallapu, Jekan Thangavelautham
(*University of Arizona/SpaceTREx*)

There are estimated to be more than two million small bodies such as asteroids and comets in the solar system. Exploring asteroids and comets are of critical importance to understand the origins of the solar system. In addition, these small-bodies can provide answers to the origin of water, organic chemicals and life. A second motivation is for impact-hazard monitoring and security and finally a third motivation is for resource prospecting. Asteroids and comets present unique engineering challenges both for on-orbit and surface exploration. A major challenge is that their low-gravity which requires precise positioning and very low-thrust maneuvering. A second challenge is that the asteroids are irregularly shaped objects, so the gravity potential is complex. This makes the motion of the spacecraft non-Keplerian and can exhibit chaotic motion. Finally, a third challenge arises from the trajectory perturbation arising due to solar radiation pressure in the absence of a strong gravity field. Existing missions and literature has focused heavily on asteroid rendezvous, surface operations, and escape trajectories, limited work exists on low-cost proximity operations around asteroids. Our work seeks to exploit the low-relative cost of flybys and the natural perturbation in an asteroid gravity field to perform complete mapping of an asteroid by minimizing fuel use. The work proceeds by analyzing the equations of spacecraft motion around the asteroid to obtain stable and semi-stable trajectories. Among these stable trajectories, an optimal trajectory can be selected to meet the mission objectives. This is demonstrated by designing optimal trajectories to an asteroid for a surface mapping mission. Finally, this work lays a systematic foundation to the trajectory design problem around asteroids, and shows pathways to design optimal trajectories for a swarm of spacecrafts. The coupled attitude and trajectory of a swarm is analyzed to optimize overall system performance.

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

Randa Relich Milliron (*Interorbital Systems*)

The expense of buying passage for a small satellite payload is often more than a small business or an academic institution can afford, and usually more than a government or military entity would like to spend. Waiting for an opportunity to launch as a secondary payload is often a frustrating, if not endless process. Global competitions among hundreds of student satellite projects for these rare flights leave all but the one or two lucky winners without a ride to orbit. An inexpensive, dedicated launcher; an assortment of affordable small satellite kits; and low-cost, rapid-response launch services are urgently needed to create and carry small experimental, academic, government, art, and military payloads to orbit. Interorbital Systems' (IOS) NEPTUNE modular rocket series: N1; N3; N5; and N8 LUNA; and IOS' Personal Satellite Kits will fill those needs. For example, the N5 is designed to launch 24 picosats at a time, for as little as $8,000 each, or from $1.5 million for a single dedicated 30-kg payload capacity. The popularity of this new service is evidenced by Interorbitals current orbital launch manifest of 146 picosats for upcoming sold-out LEO Missions I-V. Flight-testing continues with orbital launches beginning summer of 2018, date license-dependent, plus a Q4 Moon mission: the Lunar Bullet Impactor. A spring suborbital flight of the major NEPTUNE component, the CPM 2.0, carrying a manifest of 11 small-sat payloads for testing under flight conditions is planned. IOS will be testing its own guidance and control systems with the upcoming launch that will also provide the platform for demonstrating and flight-testing significant science applications and breakthrough technologies like the Wayfinder II Mission. Wayfinder II is a 3U CubeSat and hosted payload platform designed and integrated by Boreal Space, NASA Ames Research Park. The overarching mission of Wayfinder II is to raise the Technology Readiness Level (TRL) of technologies that are key to space science, exploration, and commerce. Boreal has created a unique hosted payload architecture that will house and flight-test the following four high-profile payloads aboard its Wayfinder II: 1. Spacelink Secure UHF radio, developed by Boreal and Danish Space Inventor. 2. SHARK Payload provided by the Stanford University Extreme Environments Laboratory (XLAB) 3. Graphene Experiment supplied by the Centre for Advanced 2D Materials, National University of Singapore. 4. Robotics Payload provided by Team Hakuto, ispace, inc. Several IOS experiments and 3 Mexican payloads are also aboard.

C.5 Modular Solar Steam Propulsion Units for Interplanetary Applications

Jorge Martinez Dominguez, Jekan Thangavelautham
(*University of Arizona/SpaceTREx*)

Small-spacecraft and CubeSats are on the verge of being interplanetary explorers. They offer the promise of low-cost launches and can open new paradigms in planetary exploration, particularly high-risk, high-reward mission opportunities. However, persistent challenge with interplanetary CubeSats is the lack of a reliable and proven propulsion system. State-of-the-art chemical propulsion systems for small satellites, such as green monopropellant and hydrazine perform combustion, but produce high-thrust and high delta-v. Combustive propulsion units present additional risk to a mission that presents challenges integrating them as secondary or tertiary payloads. Electric propulsion systems such as hall-thrusters produce high Isp but require high-power, typically relying on large solar panels and produce very low thrust. Very low-thrust propulsion system present important challenges, typically lengthening a mission and needed delta-v and they present additional challenges in terms of performing planetary capture. A system with the potential of offering high-thrust and high-Isp offer substantial benefits. Water-steam is one such candidate that has been the focus of our studies for several years. Our efforts are focused on using solar thermal concentrators to heat water into high-temperature steam. These solar thermal concentrators utilize carbon-nanoparticles such as Vantablack that enables capture of 99.9incoming light into heat. Vantablack is particularly advantageous as its provides point source heating of water into steam even at low-background temperatures. However, water-steam based propulsion steam imposes major design requirements on an interplanetary spacecraft including use of steerable concentrators, additional piping and heat exchange to collect and throttle the steam for propulsion. Alternate options include using conventional triple junction panels to electricity to heat water into steam. This option is compact but offers substantially reduced operational efficiencies. In our updated spacecraft concept, we develop simplified steering mirrors and concentrators for use on a 24U CubeSats or ESPA-class spacecraft. In addition, detailed flow physics of the concept is performed using ANSYS. This is being used to study any multi-phase changes during the expansion and analyze the real efficiency and thrust of the system. Further work is being done to modularize the thrusters, enabling several smaller modular unit thrusters instead of a single large thruster to enable steering and multi-mode operation, including high-thrust and high-Isp operation using separate units.

C.6 Cubesatellite Replication of Deep Space Fuel Transfer

Nikunj Patel, Anna Sifferath, Abarneel Dutta
(*JPL/Caltech*)

One of the biggest issues in space travel derives from the Tsiolkovsky rocket equation which states that the total change in the spacecraft velocity for a given burn is a function of the rockets exhaust velocity, and a logarithmic difference of the spacecrafts mass at the beginning and after the burn. Consequently, in order to transfer very heavy payloads into Geostationary Earth Orbit (GEO) and beyond, rockets are required to carry a proportionally large mass of propellant to achieve the desired orbit. However, this phenomenon results in an engineering dilemma: if additional propellant is needed for a flight, the rocket must now become larger to compensate for the added propellant volume; which adds more mass, and in return causes a need for more fuel. As a result, a large percentage of the total propellant used for a flight is used just to get the rocket out of the Earths atmosphere [1]. For example, the 1 st stage of the Apollo mission had a burn time of only 150 seconds, but used about 77% of the total initial mass (about 2.2 million kg!) of the Saturn V [2]. Consequently, research into propellant tank depots was begun as a solution to this launch mass problem, as it will enable spacecraft to refuel in orbit. This would allow for greater travel distances and heavier payloads with smaller launch vehicles. The goal of the proposed paper would be to design a cube-satellite mission for preliminary research to understand propellant fuel transfer in space. Two 3U cubesatellites will be designed to rendezvous in Low Earth Orbit (LEO) and undergo docking maneuver utilizing active attitude control maneuvers. Utilizing high definition cameras and VHF downlink/UHF uplink Full Duplex Transceiver, useful information regarding fuel transfer would be collected. It will provide research data in a low-zero gravity environment that would aid with the creation of fuel depots in deep space. In addition to that, the proposed work would aid humanitys goal in developing technology to become Earth independent.

References:
[1] "14.2 The Rocket Equation," 14.2 The Rocket Equation http://web.mit.edu/16.unified/www/fall/thermodynamics/notes/node103.html
[2] "Saturn V Flight Manual," Aug. 1969

C.7 Essentially Free: Shipping from Asteroids, Moons and Planets to Earth

Darrin Taylor
(*Outer Space Colonization*)

Transportation costs are what hampers humans from exploiting the unlimited riches of space.

Changes in launch methodologies are beginning to change the economics but a much larger change looms in the next 50 years.

Economically, space commerce is only expensive in terms of Earth dollars because Earth resources are required to navigate in space. If navigation in space could be achieved completely with in-situ non-terrestrial resources it would be possible to sell Lunar soil for similar prices as Earth soil and make a profit in terms of Earth dollars.

This talk will be primarily economic and discuss the Infrastructure that would need to exist on Mars or the Moon in order to facilitate the trade of extra-terrestrial soil at a price point that would be competitive with Earth soil. This trade example represents the cheapest imaginable item of trade with the worst profit margin and the highest mass/value.

A brief look at reusable rockets, fuel from water, mass drivers and solar sail derivatives will be performed. The focus will be on the lowest cost of initial ownership and on system lifetime cost/complexity.

The engineering decisions presented are unlikely to be the correct ones. But 100-200 years from now a system very similar to the one presented may allow transportation costs to and from the moon, asteroids or Mars to be lower than Transportation costs within the Earth.

D.1 Cupid's Arrow – a Small Interplanetary Probe Concept

Anthony Freeman, Christophe Sotin, John Baker
(*JPL/Caltech*)
Guillaume Avice (*Caltech*)

Cupid's Arrow is a small atmospheric probe concept designed to measure noble gases and their isotope ratios in the atmosphere of Venus. The Venus Exploration Analysis group (VEXAG) has placed a high priority on such measurements in its "Goals, Objectives, and Investigations" document (2014). Since noble gases are tracers of processes affecting planetary evolution, determining their concentration and isotope ratios in Venus atmosphere answers questions on how Venus has evolved. By comparing the values for Earth, Mars, and primitive bodies, these data can provide clues on why Earth and Venus, two planets with similar composition, size, and distance to the Sun, have evolved so differently.

The nominal Cupid's Arrow mission assumes that the probe is targeted to Venus and carries a Solid Rocket Motor (SRM) that puts it into orbit around with periapsis below the homopause where noble gases are well mixed within the CO2-N2 atmosphere. Four samples of the Venus atmosphere can be captured at each pass. Each sample is then analyzed by a miniaturized Quadripole Ion Trap Mass Spectrometer (QITMS) developed at JPL. A calibrant tank provides a reference for calibration. Data are transmitted to Earth during the long apoapsis segment of the orbit. The study estimates the mass of the dry probe as 70 kg, including margins.

This paper will address the design of the Cupid's Arrow mission and spacecraft concept.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Funding to mature the concept was provided under NASA's Planetary Deep Space Smallsat Studies program.

D.2 Primitive Object Volatile Explorer (PrOVE) – Waypoints and Opportunistic Deep Space Missions to Comets

Tilak Hewagama (*University of Maryland/NASA GSFC*),
Pamela Clark (*JPL/Caltech*), Shahid Aslam (*NASA GSFC*),
Michael Daly (*York University*),
Ben Malphrus (*Morehead State University*), David Folta (*NASA GSFC*)

Primitive Object Volatile Explorer (PrOVE) is a CubeSat mission concept to study the surface structure and volatile inventory of comets in their perihelion passage phase when volatile activity is near peak. CubeSat infrastructure imposes limits on propulsion systems, which are compounded by sensitivity to the spacecraft disposal state from the launch platform and potential launch delays.

We propose circumventing launch platform complications by using waypoints in space to park a deep space SmallSat or CubeSat while awaiting the opportunity to enter a trajectory to flyby a suitable target. Waypoints are a novel solution to enable exploring new comets, since a fully functional spacecraft can be directed to an encounter with reasonable lead time following discovery – otherwise infeasible with conventional spacecraft, which have only been able to visit short-period comets on well-known orbits. In our Planetary Science Deep Space SmallSat Studies (PSDS3) program, we investigated scientific goals, waypoint options, potential concept of operations (ConOps) for periodic and new comets, spacecraft bus infrastructure requirements, launch platforms, and mission operations and phases. To achWe do not know the origin of the Martian moons Phobos and Deimos. One set of hypothesesieve 'waypoints', missions such as PrOVE can be launched aboard a NASA, DoD, or NOAA LEO, MEO, or GTO EELV rideshare mission and use the launch vehicle's excess capacity to reach escape, or near escape, velocities. A series of lunar and/or Earth flybys can increase apogee to permit a comet flyby.

We have designed a CubeSat science payload to return unique data not obtainable from ground-based telescopes and to complement data from Earth-orbiting observatories. The PrOVE mission will (1) acquire 5-10 m resolution surface maps, (2) investigate chemical heterogeneity of a comet nucleus by quantifying volatile species abundance and changes with solar insolation, (3) map the spatial distribution of volatiles and determine any variations, and (4) determine the frequency and distribution of outbursts.

The low-risk and highly versatile multispectral Comet CAMera (ComCAM) on PrOVE targets We do not know the origin of the Martian moons Phobos and Deimos. One set of hypothesesthe most important cometary volatiles: H2O, CO2, CO, and organics; CO2 is observable only from space due to telluric extinction. These molecules are best probed by their non-thermal fluorescence signatures in the 2-5 μm Mid-Wave InfraRed (MWIR) spectral region, which PrOVE will use to map all four species simultaneously. Thermal emission dominates spectral wavelengths $>$5 μm in the inner coma, which enables PrOVE to map the inner coma temperature distribution by measuring 7-10 and 8-14 μm Long-Wave InfraRed (LWIR) emission. At closest approach, the flyby will discriminate measured quantities at a spatial resolution of $\sim$0.3 km, comparable to 0.005 arc seconds angular resolution for a ground-based observatory on a comet $\sim$107 km from Earth.

D.3 PRISM: Phobos Regolith Ion Sampling Mission with Compact SIMS

Michael Collier (*NASA GSFC*), Pamela Clark (*JPL/Caltech*),
William Farrell (*NASA GSFC*), Micah Schaible (*Georgia Tech*),
Ben Malphrus (*Morehead State University*), David Folta (*NASA GSFC*)

We do not know the origin of the Martian moons Phobos and Deimos. One set of hypotheses holds that they formed in the outer solar system or outer asteroid belt and were captured later by Mars [Burns, 1992; Ivanov, 2004], while others maintain that they formed in-situ near Mars, from a circum-Mars disk left over at the formation of Mars [e.g., Rosenblatt et al., 2016; Peale and Canup, 2015] or formed as a result of a giant impact [Craddock, 2011]. These two broad classes of hypotheses predict different compositions. Resolving the question of origin for the Martian moons Phobos and Deimos requires far more definitive information on their composition. Current information is based largely on infrared spectra that are inconclusive due to the lack of strong diagnostic features. The JAXA MMX mission will obtain definitive compositional measurements for Phobos using in-situ gamma-ray, or neutron spectroscopy. Laboratory work has clearly shown that the composition of surfaces can be determined remotely using a compact SIMS instrument to detect solar wind sputtered secondary ions by using relative secondary ion yields measured in experiments and known surface compositions for the laboratory samples (Dukes and Bargiola, 2015; Schaible et al, 2017). Here we describe a smallsat mission called the Phobos/Deimos Regolith Ion Sample Mission (PRISM) that will utilize a high-resolution TOF plasma composition analyzer to make SIMS measurements by observing the sputtered species from various locations of the moons' surfaces. The SIMS technique and ion mass spectrometers in general complement and expand quadrupole mass spectrometer measurements by collecting ions that have been energized to higher energies, 50-100 eV, and making measurements at very low densities and pressures. Furthermore, because the TOF technique accepts all masses all the time, it obtains continuous measurements and does not require stepping through masses. The instrument will draw less than 10 W and weigh less than 5 kg. The spacecraft, nominally a radiation-hardened 12U CubeSat, will use a low-thrust Solar Electric Propulsion system to send it on a two-year journey to Mars, where it will co-orbit with Deimos and then Phobos at distances as low as 27 km.

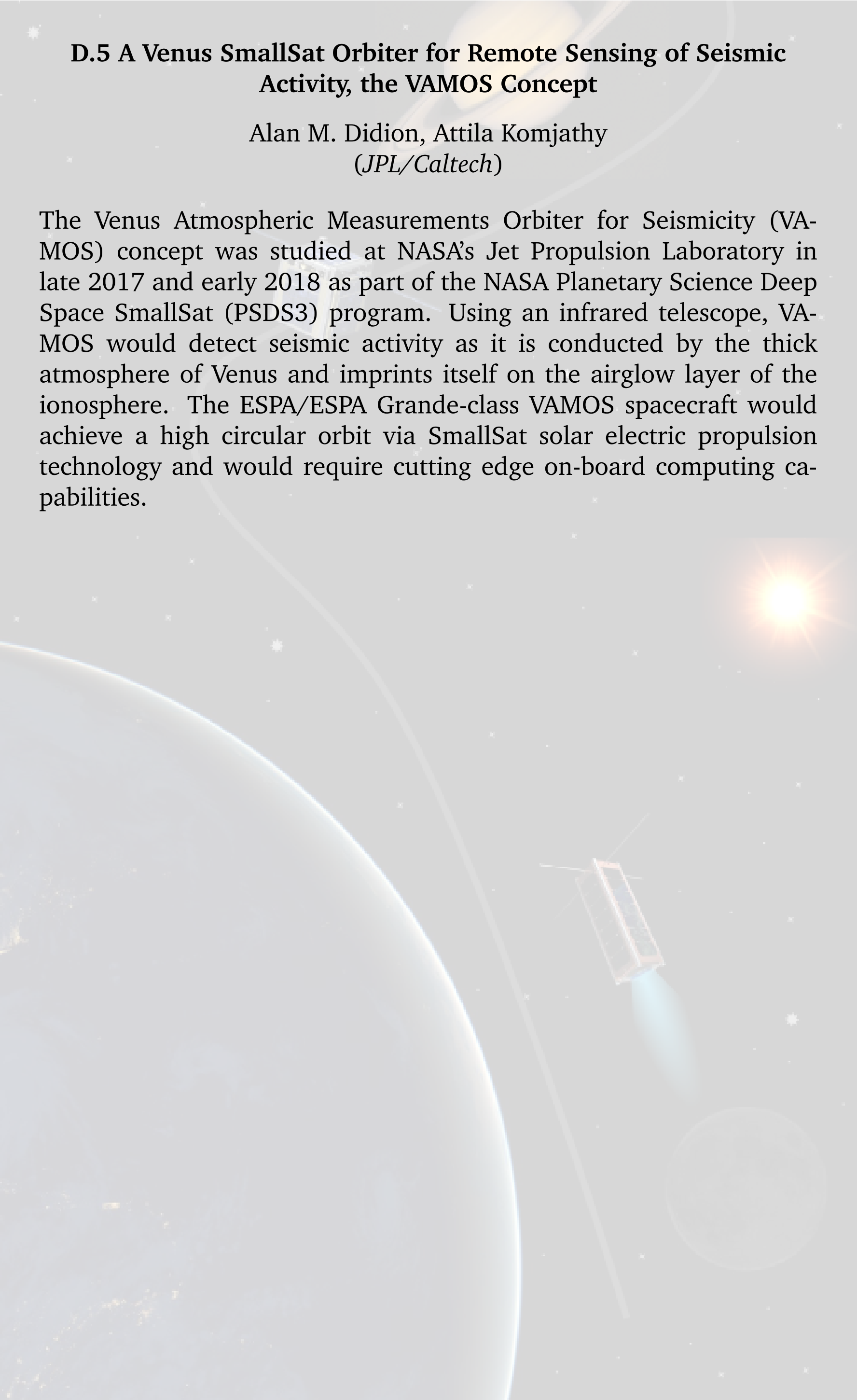
D.4 ZodiScout: A Small Satellite to Explore the Origins of the Interplanetary Dust in our Solar System

Varoujan Gorjian, Nela Turner, Hien Nguyen, Kieth Grogan, Geoffrey Bryden
(*JPL/Caltech*)

ZodiScout is a 6U cubesat to image and take spectra of the zodiacal dust as it flies out to 5AU and then above the ecliptic plane to create the best map of our solar system's dust to date.

Even though the zodiacal light was known to the ancients, its origin and structure are still not well established. The zodiacal light is sunlight scattered and re-emitted off the dust cloud in our solar system and the zodiacal cloud's shape traces the long-term dynamics of small solar system bodies. It is replenished depending on the rate of comet in-fall towards the Sun, and how often asteroids collide, rates that are hard to establish otherwise. But most importantly the source and rate of production of the dust set limits on the amount of material in the Kuiper belt and Oort cloud, which are among the best-preserved remnants from the formation of the solar system, but which we have little to no access. Despite the zodiacal cloud's importance, and even after significant advances in measurement, we have yet to establish how much dust is present overall, exactly how the dust is distributed across the solar system, and, most importantly, the balance between the cometary and asteroidal dust that compose the cloud.

ZodiScout will need to launch with an outer planets mission. Once the mission has achieved a velocity sufficient to reach an outer planet like Jupiter, the cubesat will detach and fly independently. On its trip out of the inner solar system, it will take images and low-resolution spectra (R 100) in the optical to trace the light scattered by dust (which helps constrain the sizes of the smaller grains) and in the near-IR to trace the light emitted by dust (which traces larger grain sizes). High-resolution spectra ($R\sim3000$) will be taken of the solar Fraunhofer lines scattered by the dust to distinguish it from background light so as to set the absolute amount of dust. Reaching Jupiter, Zodiscout will use a gravity assist to redirect it out of the Ecliptic plane. By leaving the inner solar system and then the ecliptic plane, ZodiScout will venture through regions with combinations of asteroidal dust, cometary dust from the Kuiper Belt and cometary dust from the Oort Cloud, and interstellar dust, allowing the it determine the contribution of each source to each region as well as creating the most comprehensive map of dust in our solar system.



D.5 A Venus SmallSat Orbiter for Remote Sensing of Seismic Activity, the VAMOS Concept

Alan M. Didion, Attila Komjathy
(*JPL/Caltech*)

The Venus Atmospheric Measurements Orbiter for Seismicity (VAMOS) concept was studied at NASA's Jet Propulsion Laboratory in late 2017 and early 2018 as part of the NASA Planetary Science Deep Space SmallSat (PSDS3) program. Using an infrared telescope, VAMOS would detect seismic activity as it is conducted by the thick atmosphere of Venus and imprints itself on the airglow layer of the ionosphere. The ESPA/ESPA Grande-class VAMOS spacecraft would achieve a high circular orbit via SmallSat solar electric propulsion technology and would require cutting edge on-board computing capabilities.

D.6 MISEN: The Mars Ion and Sputtering Escape Network

Robert Lillis, Shannon Curry, Davin Larson
(*UC Berkeley Space Sciences Laboratory*)
Christopher Russel (*UCLA Dept. of Earth and Space Sciences*)
David Curtis (*UC Berkeley Space Sciences Laboratory*)
Jeff Parker (*Advanced Space LLC*)

Ion escape and sputtering escape of atmosphere have played important roles in the history of Martian. climate and habitability, as drivers for its evolution from a planet where liquid water was at least episodically stable, to the cold, arid planet we see today. The MAVEN mission has substantially improved our understanding of these processes over the last two years by providing measurements of planetary ions (escaping from, and precipitating into, the Martian atmosphere) and intermittent sampling of the upstream solar wind conditions that drive these processes

However, MAVEN is fundamentally limited by its single measurement platform: a) spatial and temporal variations in escape fluxes cannot be distinguished from one another, b) responses of escape fluxes to changing solar wind conditions (typically ∼1 minute) can only be measured with a time-lag of an hour or more (if at all) and c) global escape rate variability in response to space weather "storms", much more common and intense in the early solar system, must be estimated (poorly) from a single orbit track.

MISEN's objectives are to characterize the global patterns, variability, and real-time response to changing solar wind conditions, of ion and sputtering escape at Mars. MISEN consists of 3 identical spacecraft in complementary elliptical orbits around Mars, each measuring magnetic field and electron and ion energy spectra and angular distributions, ensuring global coverage of both the precipitation and escape of planetary heavy ions from Mars, as well as >95% coverage of upstream solar wind conditions. The three spacecraft will separate from the ESPA ring after a trans-Mars injection burn and cruise via a constant-thrust trajectory to a Mars rendezvous in under two years. The MISEN Science payload consists of: a) Magnetometer, accommodated on a folding boom b) Ion spectrometer, with mass discrimination, to detect precipitating and escaping planetary ions c) Electron spectrometer, to determine magnetic topology. A foldable antenna and IRIS radio will transmit science data directly back from Mars orbit without the need for relay from existing Mars assets. Mission operations are simple, with the spacecraft spinning in order to collect fully three-dimensional plasma data. No special pointing is required except during downlink. In summary, MISEN will provide simultaneous multi-point measurements of the plasma environment in near-Mars space, building on MAVEN's legacy for a fraction of the cost, and revealing for the first time the global patterns of ion and sputtering escape, and how and why they vary.

D.7 Deep Space 9 Mission Concept – Secondary Payload Study for the proposed Next Mars Orbiter

Bogdan Oaida (*JPL/Caltech*)
Tod Schulter (*University of Michigan*)

Deep Space 9 (DS9) is a proposed CubeSat-based distributed architecture for the exploration of the Martian surface and atmosphere. It is envisioned to complement and enhance the capabilities of the proposed Next Mars Orbiter (NeMO), a spacecraft concept currently under study as a potential future NASA orbital communication and reconnaissance mission to Mars in the 2020s. For the DS9 study, various NeMO concept parameters and capabilities were assumed. For instance, NeMO could potentially have the capability to carry and deploy secondary payloads into Mars orbit. The DS9 concept assumes and leverages this potential capability to eliminate the need for a dedicated launch vehicle and the propulsive/navigational capability necessary to achieve Mars orbit independently. DS9's use of a distributed architecture would introduce unprecedented coverage and revisit time to Mars climatology science, and could enable frequent high-fidelity radio sounding of the planets lower atmosphere. Furthermore, it would constitute an excellent validation of various technologies currently under development by JPL and partner institutions to make deep space exploration accessible to CubeSats.

The hypothetical DS9 constellation would consist of four 6U CubeSats in low-Mars orbit that image the surface and atmosphere of Mars in nine spectral bands, and two additional 6U CubeSats in high-Mars orbit to enable radio occultation sounding of the atmosphere by transmitting to the CubeSats below. These observations would enable the characterization of the processes that control the distribution of dust and volatiles in the lower atmosphere as well as define the mechanisms by which these exchange between the surface and atmosphere. Furthermore, they would help determine the characteristics of the atmosphere that affect EDL designs and that may pose a risk to ascent vehicles, ground systems, and human explorers. Successful completion of these science objectives would further NASA's goal of characterizing the state of the present climate of Mars' atmosphere and its underlying processes, as well as the goal of obtaining knowledge sufficient to design and implement a human mission to the Martian surface within acceptable cost, risk, and performance parameters. Lastly, the mission concept would utilize mostly COTS parts and an updated version of the high-heritage Mars Color Imager (MARCI) instrument as the principal science payload. In doing so, Deep Space 9 would accomplish its objectives within minimal cost and risk levels.

E.1 Progress Update on the Morehead State University Ground System Development for Interplanetary CubeSat Missions

Benjamin Malphrus, Jeff Kruth,
(*Morehead State University*)
Timothy Pham, Jay Watt
(*JPL/Caltech*)

CubeSats and small satellites are increasingly being used in interplanetary research. The 13 CubeSats slated to fly on the NASA's Exploration Mission-1 (EM-1) in 2019 will open the door for CubeSat and smallsat exploration of the solar system. As these CubeSat missions venture to the distance of the moon and beyond to other bodies within the Solar System, they require a ground tracking system with greater capabilities than the systems currently support CubeSats in low Earth orbits. Performance attributes such as large aperture, low noise temperature, low processing loss, high transmitting power, operating at higher performance X-band, use of highly efficient forward error correction codes, become more and more important in enabling communication with interplanetary spacecraft.

Under the support of the NASA Advanced Exploration Systems (AES) program and in partnership with the NASA Deep Space Network (DSN), the Morehead State University 21-m antenna is being upgraded to provide tracking support to the EM-1 Lunar IceCube mission, and likely to other EM-1 Cubesat missions. The Morehead ground station will have full telemetry, tracking and command capability, most suitable for deep space communications. Equipped with instrumentation developed by the DSN, the Morehead ground station will have the same data interfaces with mission operation centers as with the DSN. Mission users will receive telemetry and radiometric data that are tracked by Morehead State University and relayed to the Deep Space Operation Center (DSOC) at the Jet Propulsion Laboratory (JPL). For commanding, the mission operations center will directly connect to the uplink equipment at Morehead system, again the same way as with other DSN antennas. Telemetry, tracking and command data interfaces are fully compliant with the CCSDS space link extension standards.

At the ISSC 2017, a system architecture of the Morehead ground system and development plan were presented. In this presentation, we provide an update on the progress made over this past year. A portion of the ground station, comprised of digital signal processing equipment, has been installed and tested locally. The test design for telemetry, command and radiometric verification is discussed in details. These tests serve building blocks for later more expansive testing that include the front-end RF equipment as well as components at JPL. Current development and deployment of the RF front-end components will also be discussed. We will also reflect on the status of connection to the NASA mission network backbone, which will enable end-to-end data flow between components at Morehead and JPL.

In addition, we will describe our plan in testing the system with spacecraft that are currently in operation. We will discuss the considerations given to selection of spacecraft that are suitable to the Morehead system testing. Such a plan includes testing with the Mars Cube One (MarCO), one of the NASA first interplanetary cubesats.

E.2 Deployable Faceted Cassegrain Reflectarray Antenna for CubeSats

Asa Darnell
(*MMA Design LLC*)

The need for large radio frequency (RF) apertures in space has long driven technology developments that enable aperture sizes that exceed the allowable volume within a launch vehicle fairing. MMA has been developing and increasing the TRL of deployable thin film (membrane) antenna architectures in order to achieve unparalleled stowage efficiency and deployed aperture size. Reflectarray antenna architectures lend themselves to using tensioned membranes, however the trade-offs associated with reflectarray performance such as limited bandwidth come into play. By utilizing a facetted system architecture, this bandwidth reduction can be minimized in order to increase overall antenna performance by more closely mimicking a parabolic shape. With the additional variable of facet angle and parabolic approximation, MMA is able to tune the antenna system parameters to mission objectives. Along with the facetted design, MMAs enabling technologies such as composite tape booms, innovative drivetrains, reflectarray membranes, and miniature launch restraints allow the Tape-actuated High Gain Reflectarray (T-DaHGR) to stow in volumes small enough to be utilized on nanosatellites as small as 3U (10cm x 10cm x 30cm). Leveraging these technologies also allows the T-DaHGR system to be deployed using a single motor drivetrain after launch lock release. The current highest fidelity design is nearly ready for manufacture and is able to produce a 1m2 aperture from a 1U volume for use at C-X bands (8-10 GHz). By providing such large apertures and simple deployment schemes to cubesats, MMA plans to enable the small satellite market with remote sensing and communications capability once thought impossible. An X-band T-DaHGR is currently slated for flight in December 2019 for providing a high data rate downlink and proving out deep-space communications aboard a university-designed cubesat.

E.3 DTN for Interplanetary SmallSat Missions

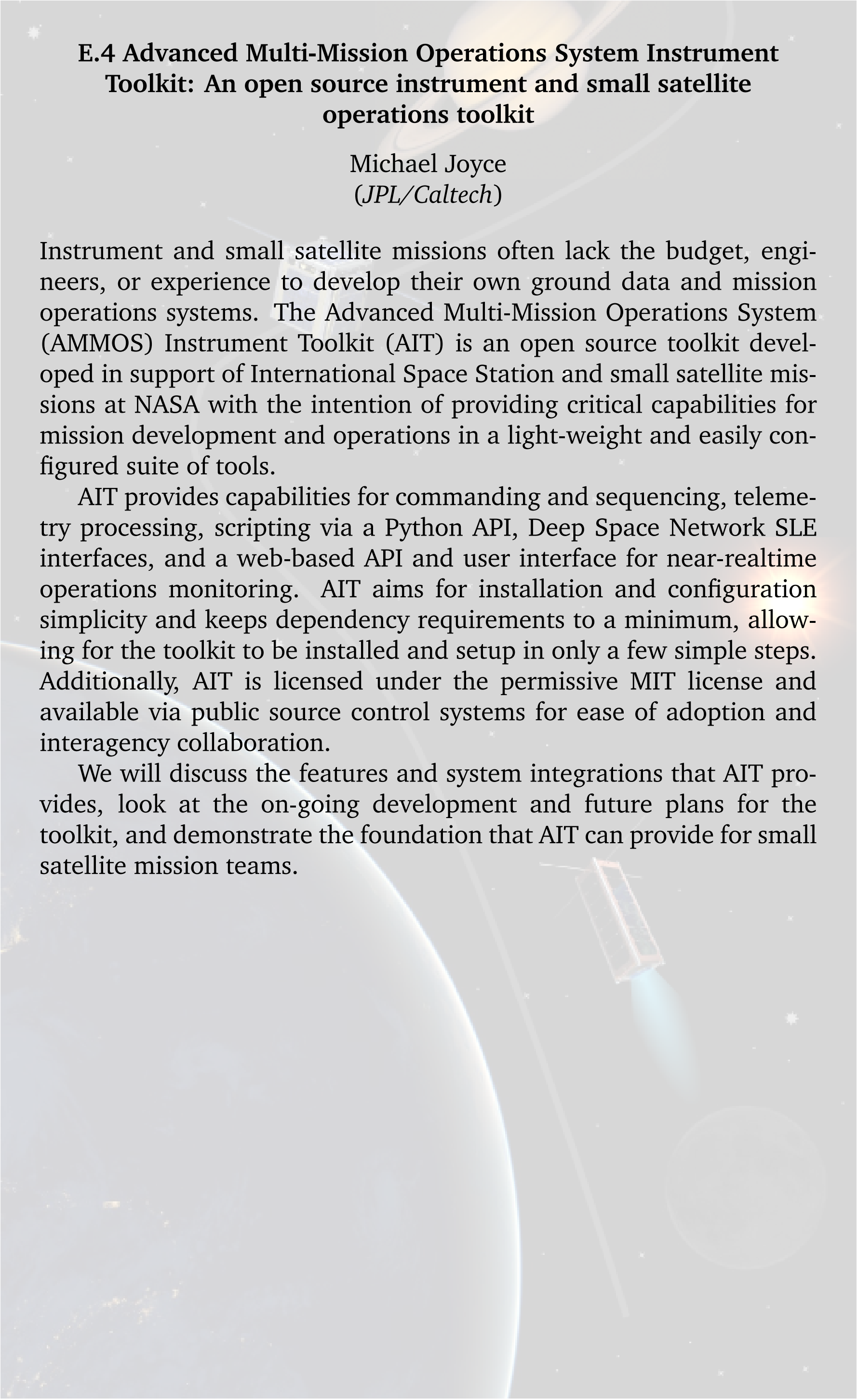
Nate Richard (*Morehead State University*)
Leigh Torgerson (*JPL/Caltech*)
Brenda Lyons (*NASA Johnson Space Center*)
Jay Wyatt, Scott Burleigh, Gregory Miles (*JPL/Caltech*)

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

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

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

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



E.4 Advanced Multi-Mission Operations System Instrument Toolkit: An open source instrument and small satellite operations toolkit

Michael Joyce
(*JPL/Caltech*)

Instrument and small satellite missions often lack the budget, engineers, or experience to develop their own ground data and mission operations systems. The Advanced Multi-Mission Operations System (AMMOS) Instrument Toolkit (AIT) is an open source toolkit developed in support of International Space Station and small satellite missions at NASA with the intention of providing critical capabilities for mission development and operations in a light-weight and easily configured suite of tools.

AIT provides capabilities for commanding and sequencing, telemetry processing, scripting via a Python API, Deep Space Network SLE interfaces, and a web-based API and user interface for near-realtime operations monitoring. AIT aims for installation and configuration simplicity and keeps dependency requirements to a minimum, allowing for the toolkit to be installed and setup in only a few simple steps. Additionally, AIT is licensed under the permissive MIT license and available via public source control systems for ease of adoption and interagency collaboration.

We will discuss the features and system integrations that AIT provides, look at the on-going development and future plans for the toolkit, and demonstrate the foundation that AIT can provide for small satellite mission teams.

E.5 Structurally reconfigurable modular inflatable reflectors

Arman Chandra (*Univ. of Arizona/SpaceTREx*)
Alessandra Babuscia (*JPL/Caltech*)
Jekan Thangavelautham (*Univ. of Arizona SpaceTREx*)

Deep space communication and tracking are key technology enablers for interplanetary CubeSats. There are two widely investigated strategies towards realizing a CubeSat based interplanetary communications system. The first, is the development of deployable antennas that can be stowed within a Cubesat. The typical requirements for a science focused mission being a minimum of 28 dBi for the X-band and 42 dBi for the Ka band. The second, is the development of communication strategies that co-operatively utilize a secondary relay network or pre-existing deep space assets. Deployable technologies in development for CubeSats include reflect-arrays, mesh reflectors and inflatables. Inflatables show the most potential in terms of packing efficiency and an ability to be scaled up to large sizes employing minimal mechanisms and mechanical complexity. Among the challenges involved in enabling co-operative CubeSat communications in deep space is the ability to minimize losses and adapt to changing scenarios. Structural reconfiguration can greatly enhance cooperative communication as it enables modulation the antennas electromagnetic behavior. This is achieved through adaptive re-shaping of the reflectors surface. This can be utilized to tune the CubeSat's antenna with existing deep space communications infrastructure or provide patterned electromagnetic coverage over a swarm of CubeSats. Previously developed structurally reconfigurable antennas employ mechanical linkages and actuation systems greatly restricting their ability to be stowed compactly. This work investigates the usage of modular inflatable assemblies towards achieving structural reconfiguration. We build up on our previous work on passively activated modular inflatables to come up with candidate assemblies utilizing composite inflatables that contain both hard and soft inflatable units. A study is conducted to understand performance requirements for interplanetary communications and the extent of reconfiguration achievable through inflatables. Our studies are carried out using a finite element structural model of the inflatables in conjunction with numerical electromagnetic solvers.

E.6 Recent Developments in Small Satellite Antenna Technology

Richard E. Hodges
(*JPL/Caltech*)

Small Satellites are a rapidly growing sector of the space industry with continued progress driven by new technologies that enable these satellites to perform imaging, remote sensing and science missions. Until recently, missions such as these were only possible with larger satellites. Antennas are one of the key enabling technologies that drive this growth. The inherent stowage limitations, mass restrictions and environmental conditions imposed by small satellites present a unique antenna design challenge. These limitations are particularly acute for satellites designed for interplanetary missions because the need for additional solar panels, propulsion requirements, lack of GPS, etc. require packing additional hardware into the limited small satellite volume. This is particularly acute for two classes of antenna: High Gain Antennas (HGA) and low frequency antennas. HGAs operate in higher frequency bands (e.g. X, Ku, Ka-band) and require a large physical aperture size which must be stowed for launch and deployed on orbit. This has led to the development of a variety of new HGA antenna designs and deployment mechanisms adapted to the unique requirements of small satellites. At low frequencies (HF, VHF, UHF) even electrically small antennas may be physically large in comparison to a CubeSat bus, and therefore require stowage and deployment.

This paper presents an overview of recent small satellite antenna developments with an emphasis on deployable HGA and low gain proximity antenna technology. Significant new HGA technologies include novel deployable mesh reflectors, flat folded panel reflectarrays, inflatable antennas and membrane antennas. Examples of these antenna technologies will be described and the relative advantages, drawbacks and current Technology Readiness Level of each will be presented. Special attention will be given to historically important breakthrough high TRL antennas in order to illustrate their relative merits and applicability. A number of other recent antenna developments and emerging technologies will also be presented to illustrate future trends in antenna development for small satellite communications and instruments.

F.1 New Avenues for Planetary Science Using On-Orbit CubeSat Centrifuges

Erik Asphaug (*Univ. of Arizona/LPL*)
Jekan Thangavelautham (*Univ. of Arizona/SpaceTREx*)

There are thousands of asteroids in near-Earth space and millions in the Main Belt, offering many mission opportunities. Yet landing on an asteroid and manipulating its surface material remains a daunting challenge. Current missions to asteroids such as Hayabusa II and OSIRIS-REx will perform touch-and-go operations instead of landing, to limit these risks.

Fundamental research in planetary science is required to understand asteroid surface behavior, with regard to landing, mobility, and subsurface exploration. Presently we lack even the most basic knowledge, for instance whether an asteroid will act as a hard, rugged material or fluidize like quicksand under modest vibration. The same can be asked of comets and small moons.

Although similar challenges exist for determining the best form of mobility, manipulation and mechanical processing on the Moon and Mars, the milligravity environments of asteroids is unique and quite challenging to simulate. Therefore we have proposed and have been developing a low cost CubeSat mission called Asteroid Origins Satellite I (AOSat 1) that will operate in Low Earth Orbit (LEO) as a centrifuge science laboratory. The whole spacecraft will spin at 1-2 RPM, giving a 2U research chamber a milligravity environment corresponding to an asteroid the size of Itokawa. Crushed meteorites in the chamber will mimic a layer of asteroid regolith.

This approach provides a low-cost pathway to producing realistic asteroid physical and thermal conditions, for science and for engineering validation. The laboratory is equipped with cameras and piezoelectric actuators to observe and manipulate regolith. Basic experiments are planned to measure the general behavior, friction coefficient, stiction and other parameters that can feed into asteroid surface dynamics simulators.

Beyond AOSat 1, our efforts are focused on developing a series of larger, 6U CubeSats with increasingly sophisticated experiments that enable direct simulations of robotic surface landing, manipulation and resource processing/extraction. We have been developing detailed plans for instrumentation to perform penetrometery, excavate and acquire samples, process regolith and extract water.

Centrifuge science laboratories, from CubeSat and larger scales, can be used to recreate the low-gravity off-world conditions of the asteroids, Moon, Mars and other small bodies in the solar system. The laboratories can provide a persistent link to better understand and perform hypothesis-testing of planetary surface processes, being able to fully recreate them in controlled laboratory conditions on-orbit. Furthermore, this technology can be applied to de-risk next generation spacecraft technology with increased confidence and long-term planning.

F.2 Autonomous Path Planning for Climbing in Low Gravity Planetary Bodies

Steven Morad, Himangshu Kalita, Jekan Thangevelautham
(*University of Arizona/SpaceTREx*)

Large tracts of the Moon, Mars and asteroids are covered in rugged surfaces inaccessible by wheeled rovers. These include cliffs, canyons and crater walls that contain exposed rock-faces and are geological time-capsules into the early solar-system. We have proposed the SphereX robot with a mass of 3 kg, 30 cm diameter that can hop, roll and fly short distances. SphereX is robot platform composed of electronics and instruments that are being developed for CubeSats and small-satellites. A single SphereX robot may slip and fall, however, a multirobot system can work cooperatively by being interlinked using spring-tethers and work much like a team of mountaineers to systematically climb a slope. We consider a team of four or more robots that are interlinked with tethers in an x configuration. Each robot secures itself to a slope using spiny gripping actuators, and one by one each robot moves upwards by crawling, rolling or hopping up the slope. Here we present a human devised autonomous climbing algorithm and evaluate it using a high-fidelity dynamics simulator. The climbing surfaces contain impassable obstacles and some loosely held rocks that can dislodge. Under these conditions, the robots need to autonomously map, plan and navigate up or down these steep environments. Autonomous mapping and navigation capability is evaluated using simulated lasers, vision sensors. The human devised planning algorithm uses a new algorithm called bounded-leg A*. Our early simulation results show much promise in these techniques and our future plans include demonstration on real robots in a controlled laboratory environment and outdoors in the canyons of Arizona.

F.3 Guidance, Navigation and Control of SPIKE for Descent, Landing and Hopping on an Asteroid

Himangshu Kalita, Jekan Thangavelautham
(*University of Arizona/SpaceTREx*)

There are nearly 17,000 asteroids near Earth and nearly 750,000 asteroids in the main belt and counting. Asteroids are diverse in terms composition and are time capsules of the early solar system. This makes asteroids strategic locations for planetary science, resource mining, planetary defense/security and as interplanetary depots and communication relays. Landing on a small asteroid and manipulating its surface contents remains a major unsolved challenge fraught with high risk. The asteroid surface may contain everything from hard boulders to soft-regolith that are loosely held by cohesion and low-gravity. The Spacecraft Penetrator for Increasing Knowledge of NEOs (SPIKE) mission concept will utilize a small-satellite bus that is propelled using a xenon-fueled ion engine and will contain an extendable, low-mass, high-strength boom with a tip containing force-moment sensors. SPIKE will enable contact with the asteroid surface, perform regolith chemical analysis and seismology, but by keeping the main spacecraft bus at a distance. This proposed approach frees the spacecraft from having to hover above the asteroid and thus substantially reduces or eliminates fuel use when doing science operations. This enables much longer missions and missions where the spacecraft can sample from multiple locations. The proposed concept presents interesting opportunities and challenges in terms of GNC. We will present detailed dynamics and control of SPIKE for descent, landing and hopping on the surface of an asteroid. Our approach presents a finite time PD guidance law for descent and landing and then we extend it to a more robust sliding-mode controller with the use of on-board reaction wheels and propulsion. We then extend our studies to find optimal trajectories that minimize fuel consumption using machine learning techniques like evolutionary algorithms. The robustness of our optimal trajectories will be further validated with Monte-Carlo simulations. The proposed spacecraft design and controls approach is major departure from conventional spacecrafts with amphibious capabilities of a lander and flyby vehicle packaged in one.

F.4 6U deployable solar arrays for deep space missions

Vicente Diaz, Miguel Vazquez, Victor Vurgos,
Aida Auñon, Ismael Sanchez
(*DHV Technology*)

A set of deployable solar panels for 6U solar panels can achieve typically only until 20W of power generation per face when using body mounted solar array solutions. Deep Space missions, some of them with strong requirements coming from electric propulsion, needs of high power generation solutions. This work deals with the technical design, modeling, manufacturing topics and qualification of a Double deployable 6U system with high degree of technical requirements coming launchers and from the Radiation Tolerances to Van Allen belts. The aim of this work is to provide a solution for an 80W BoL system reliable and safe enough.

The chosen folding procedure of the panels allows an easy deployment and retention mechanism with five points of junction with the structure. This way of folding the panels relies on the geometry of the panel and the structure to hold the second panel in place while in stowed position, and it uses the satellite wall to lead the deployment of the second panel. The deployment inertias are compensated with both wings, introducing very little energy to the structure when deployed.

The hinges design is robust and allows a good deployment without damaging neither the panel nor the satellite. This hinges plus the rest of the design gives a strong 6U double deployable with high functionality, in addition to its light weigh, as each wing is less than 600g. Also, the design has successfully passed deployment under different temperature ranges, assuring that the panels will deploy regardless of the conditions when the satellite is launched

In terms of the circuitry for deployment purposes of the solar array, a power driver is used, which drives a power through some resistors, used as thermal knife, and cutting the retaining wire This retaining wire holds the solar panels in stowed position during the launch of the satellite, and allows the deployment with a digital signal from the on-board computer of the satellite. This system is totally tested in thermal vacuum chamber, under cold and hot cases, and vibration tests have been implemented to simulate the launch loads.

As a result, electrical performance and mechanical performance will be shown. Ground support equipment engineered for providing helping in the testing phase of the system is shown. The panels will fly in the ARGO-MOON mission to be launched from Mission 1 within the SLS Rocket in Cape Canaveral. Launch is scheduled for the end of 2019

F.5 An Advanced Packaging Approach for a High Performance Deployable Photovoltaic System R-HaWK

Eric Ruhl
(*MMA Design LLC*)

This paper presents an innovative deployable solar array power system architecture for small satellites. A system is presented that utilizes existing commercial technologies in space photovoltaics and structurally efficient material systems to realize a deployable power system. This innovation will address the need for improved stowed power density (kW/m3) and specific power (W/kg) over state-of-the-art (SOA) systems without sacrificing the structural shielding necessary for end-of-life (EOL) performance. The foundation of the innovation is a highly modular and scalable platform that combines the packaging-efficiency benefits of a blanket array with the radiation-shielding benefits of a rigid-panel array. The modular construction enables the use of automated assembly methods to reduce cost and accelerate delivery. This paper will demonstrate the feasibly of this system to improved stowed power density and EOL performance by way of unique packaging using common aerospace qualified materials and designs.

High stowed-power-density space photovoltaic systems are key technologies for enabling current and future small satellite missions. The mission scope for small satellites continues to expand beyond low earth orbit to GEO, interplanetary, and deep-space exploratory applications. The expanding spectrum of mission requirements demands a robust, reliable, and scalable power solution capable of surviving launch and high radiation environments while minimizing stowed volume. The R-HaWK architecture addresses these key requirements, specifically stowed power density (kW/m^3), specific power (W/kg) and deployed stiffness (first fundamental mode frequency). The works shown herein will demonstrate a novel path towards a next generation solar array system.

Defining a complete system is key to comparing solar array performance metrics across the multitude of array providers. The R-HaWK deployable system contains three subsystems with several components borrowed from innovations in MMA Design's deployable antenna systems and CubeSat deployable solar arrays. The individual systems include: a) a canister-free, linearly deployable boom system with exceptional packaging efficiency to deploy and support the blanket array, b) rigid composite solar array blanket system to provide superior panel stiffness and radiation shielding, and c) existing solar cell technology. Critical features of each of these components have been proven successful independently or as a subsystem, with the next major step being a conjoined system. This paper will present the results of R-HaWK trade studies performed for a range of small satellite missions up to 6 kW and compare performance with SOA solar array systems.

F.6 In-Orbit Fuel Supply: Enabling Smallsats with Extreme Delta-V

Daniel Faber
(*Space Exploration Engineering Corp.*)

Current spacecraft operations require launching spacecraft with all the fuel they will ever need. Fuel mass ratios of 2:1 to 4:1 can enable a spacecraft to depart from a LEO parking orbits to reach GEO or Mars. After arrival at an operating orbit, typical fuel mass ratios of 0.1:1 provide for lifetime operations. This paradigm defines what is seen as "normal", however it is interesting to contextualize how extraordinary this is in comparison with other transportation technologies in common usage. For example, cars massing about 1 ton consume around 40kg of fuel per week, or 20 tons over a 10-year lifetime for a fuel ratio of 20:1. Vehicles optimized for distance performance will have significantly higher lifetime fuel mass ratios. This comparison provides a glimpse of the future that can be enabled by an on-orbit supply of fuel.

Two technologies enable this new paradigm: on-orbit fuel tankers and expandable fuel tanks called FlexTanks$^{\mathrm{TM}}$. These tanks allow spacecraft to be launched without both fuel mass and tank volume and provide a very high expansion ratio. In an example implementation, a spherical FlexTank$^{\mathrm{TM}}$ with a stowed volume of 2L can expand to 60cm diameter and 100L fuel capacity (a 50:1 expansion ratio).

An example point design could be considered for a 6U CubeSat launched with tanks empty. If we assume a 10kg CubeSat mass and the above FlexTank configuration with 100L fuel, the fuel mass ratio will be around 10:1. Assuming a thruster with 2000s I_{sp} (we note that Hall Effect thrusters with power levels around 100W using low pressure, storable fuels are currently being tested and are expected to be flight-ready in 2019), a delta-V of 50 km/s is achieved. For a LEO departure at low thrust, approximately 8 km/s is required to reach Earth escape and an equal amount to return with a sample from Earth escape to LEO, leaving 34 km/s for maneuvers within the solar system. Missions enabled by such a high delta-V include sample return missions for as far away as the Main Asteroid Belt or Mercury.

The presentation will go into more detail on the in-orbit fueling architecture and the example mission concept.

9. Social Program

Dinner Reception (May 1st)
Dinner is included in the cost of registration for all conference attendees at 6:00 pm on Monday, May 7tth in the covered outdoor area opposite the exhibitor area. Meals can also be purchased for guests of attendees. All participants are encouraged to attend!

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