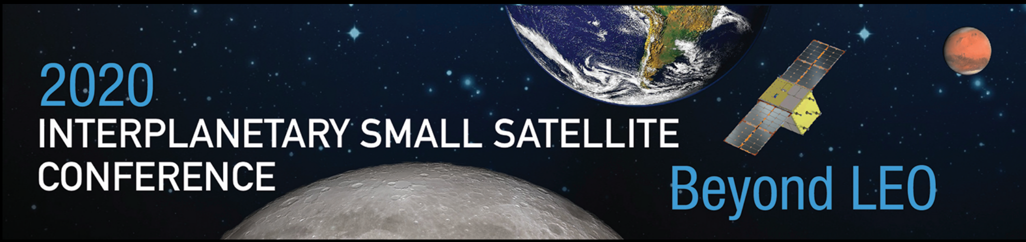
National Aeronautics and Space Administration



Conference Program

Small satellite developments in:

Artemis-I Missions and Upcoming Missions
Telecommunications, Radio Science and Ground Support
Propulsion and Launch Capabilities
New Mission Ideas and Innovative Concepts
Innovative Technologies and Instrumentation
Technologies and Mission Concepts for Extreme Environments

Hosted by:

California Institute of Technology and NASA’s Jet Propulsion Laboratory in Southern California, NASA's Small Spacecraft Systems Virtual Institute in California's Silicon Valley, and California Polytechnic State University in San Luis Obispo, California

May 11-12, 2020

www.intersmallsatconference.org

Monday, May 11, 2020

Time (PDT)	Event
9:00-9:05	**Opening Remarks: A. Babuscia**
9:05-10:00	**Keynote Speaker: F. Tan, NASA Headquarters** *Moderator: P. Clark*
10:00-10:15	Break
10:15-12:00	**Session A: Artemis-1 Missions and Upcoming Missions** *Session Chair: M. Saing*
	A.1 2020 Update for the Lunar Ice Cube Mission (*P. Clark*)
	A.2 Near Earth Asteroid Scout Mission – Status Update a Few Weeks Before Delivery! (*A. Marinan*)
	A.3 Near Earth Asteroid Scout (NEA Scout) Science Concept of Operations Utilizing Onboard Data Analysis (*J. Lightholder*)
	A.4 Lunar Flashlight Mission Overview (*D. Grebow*)
	A.5 LunaH-Map Mission Technologies and Developments (*I. Lazbin*)
	A.6 VIPER – Volatiles Investigating Polar Exploration Rover: Mission Overview (*R. Vaughan*)
	A.7 Mars Helicopter Technology Demonstration (*C. Duncan*)
12:00-12:30	**Session A Q&A Panel: S. Weston**
12:30-13:30	Lunch

Monday, May 11, 2020 *(continued)*

Time (PDT)	Event
13:30-15:15	**Session B: Telecommunications, Radio Science and Ground Support** *Session Chair: C. Lau*
	B.1 Deep Space Station 17: A University-Operated Affiliated Node on the NASA Deep Space Network Providing Telemetry, Tracking and Command Services for Interplanetary SmallSat Missions (*B. Malphrus*)
	B.2 Iris Deep-Space Transponder for Artemis Payloads (*M. Shihabi*)
	B.3 An Inter Planetary Network Enabled by SmallSats and Optical Communications (*J. Velazco*)
	B.4 Comparing Radio Occultation Results from MarCO with Mars Reconnaissance Orbiter and MAVEN: Achievable Radio Science with a CubeSat (*D. Buccino*)
	B.5 Validating the Optimization of Mission Operations for the Lunar IceCube Mission Using Delay-Tolerant Networking (*N. Richard*)
	B.6 Loop antenna on a Tree for Satellite Reception (*T. Choi*)
	B.7 Cubesat Constellation Architecture to Support Space-based Property Claims (*J. Irwin*)
15:15-15:45	**Session B Q&A Panel: A. Babuscia**
15:45-16:00	Break

Monday, May 11, 2020 *(continued)*

Time (PDT)	Event
16:00-17:30	**Session C: Propulsion and Launch Capabilities** *Session Chair: R. Nugent*
	C.1 Rocket Lab Electron and Photon-Enabled Beyond LEO Missions (*R. French*)
	C.3 Lessons Learned From the First Build of Phase Four's Maxwell Engine (*U. Siddiqui*)
	C.4 LauncherOne (*J. Fuller*)
	C.5 An Accessible CubeSat Hall Effect Thruster for Interplanetary Missions (*C. Warn*)
	C.6 Interorbital Systems: Launch Services to LEO, Luna, and Beyond (*R. Milliron*)
	C.7 FEEP Electric Propulsion Systems for Small Satellites (*D. Krejci*)
17:30-18:00	**Session C Q&A Panel: Z. Benecken**
18:00-18:05	Day 1: Closing Remarks: A. Babuscia

Tuesday, May 12, 2020

Time (PDT)	Event
9:00-9:05	**Opening Remarks: A. Babuscia**
9:05-10:00	**Keynote Speaker: V. Stamenkovic, Jet Propulsion Laboratory** *Moderator: A. Babuscia*
10:00-10:15	Break
10:15-12:00	**Session D: New Mission Ideas and Innovative Concepts** *Session Chair: A. Babuscia*
	D.1 A 200 Year CubeSat That Sings With Trees (*S. Matousek*)
	D.2 The Tree of Life: A 200-Year CubeSat (*J. Christensen*)
	D.3 SmallSat Reactive Flyby to Oort Cloud Comets and Interstellar Objects (*B. Donitz*)
	D.4 Aerial Reconnaissance of Canyons and Craters on Mars Using Sailplanes (*A. Bouskela*)
	D.5 Athena: The First-Ever Encounter of a Main Belt Asteroid with a SmallSat (*J. O'Rourke*)
	D.6 Lunar Mining Base Construction and Operation Using Teams of Small Robots (*J. Thangavelautham*)
	D.7 CubeSat-Sized Mars Solar Balloons for Aerial Exploration (*T. Schuler*)
12:00-12:30	**Session D Q&A Panel: M. Saing**
12:30-13:30	Lunch

Tuesday, May 12, 2020 *(continued)*

Time (PDT)	Event
13:30-15:15	**Session E: Innovative Technologies and Instrumentation** *Session Chair: Z. Benecken*
	E.1 Dynamic Power, SWaP reduction and Transceiver Sensitivity Enhancement in Interplanetary Small Satellites (*M. Hopkins*)
	E.2 LUNARAD – A Study of Radiation Shielding Technologies in Cis-lunar Space (*P. Faure*)
	E.3 Star Tracking for Small Satellites: Efficient Star Identification Using a Neural Network (*D. Rijlaarsdam*)
	E.4 Radiation Hardness in Magnetoresistive Random Access Memories (*D. Katti*)
	E.5 End-to-End Strategies for Exploring Lunar/Martian Caves (*H. Kalita*)
	E.6 Solar 3D Printing of Structures for Off-World Bases (*S. Anderson*)
	E.7 Use of Lasers and FemtoSats to Explore the Lunar Permanently Shadowed Regions (*A. Diaz*)
15:15-15:45	**Session E Q&A Panel: C. Lau**
15:45-16:00	Coffee Break

Tuesday, May 12, 2020 *(continued)*

Time (PDT)	Event
16:00-17:45	**Session F: Technologies and Mission Concepts for Extreme Environments** *Session Chair: P. Clark*
	F.1 Small Payloads for Lunar Exploration: Requirements and Challenges (*P. Clark*)
	F.2 100-grams High Spectral Resolution Spectrometer for SmallSat Planetary Missions (*S. Hosseini*)
	F.3 Compact QIT-Mass Spectrometers for Space Applications (*F. Maiwald*)
	F.4 Thermal Toolbox Elements for Lunar/Planetary Extreme Environments (*D. Bugby*)
	F.5 Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) (*B. Cheetham*)
	F.6 Lunar Far Side Tracking and Communication Relay System (*R. Ravikumar*)
	F.7 Smallsats Beyond Saturn Without Radioisotopes: A Preliminary Assessment (*R. Staehle*)
17:45-18:15	**Session F Q&A Panel: S. Weston**
18:15-18:20	Concluding Remarks: A. Babuscia

Contents

1. Welcome

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

Due to COVID-19, this year the conference will be entirely virtual. We have added a section on Webex tips to allow you to maximize the quality of your experience. Please do not hesitate to email us any time during the conference if you experience difficulties with WebEx or have a general question about the conference.

info@intersmallsatconference.org

This conference is organized by an evolving group of students, alumni, and staff from Caltech, JPL, NASA's Small Spacecraft Systems Virtual Institute, and CalPoly and its roots trace 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 virtually joining us.

—*The Organizing Committee*

2. WebEx and YouTube Information

WebEx Set Up Steps

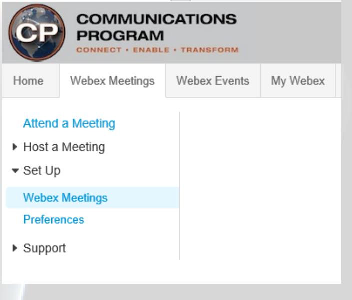
Although Webex Meetings will automatically be set up when you join a meeting, you can save time by setting up Webex Meetings, on Windows or Mac, before your meeting starts by following these WebEx set up steps:

1. Navigate to

   nasaenterprise.webex.com

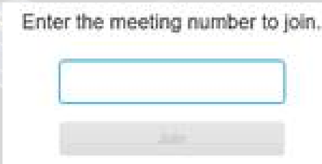
2. Click on "Set Up" in the left hand menu and click on "Webex Meetings"

3. Click on Set Up to complete the set up process

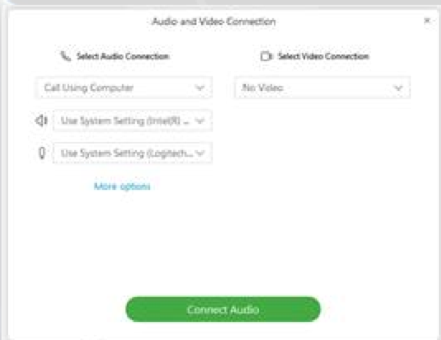


Joining WebEx Meeting

1. Navigate to nasaenterprise.webex.com
2. Enter the 9 digit meeting number from your invitation in the box provided and click join.

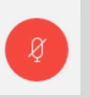


3. When prompted, enter the meeting password.
4. When entering the room, you will be asked to select your audio connection. Call using computer will use your computer speakers and microphone for audio. You can also have the system call your phone, or you can dial into the meeting using the phone. When you have made your selection, click on the green "Connect Audio" button.



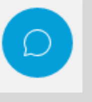
During the Meeting

1. Please keep your microphone muted unless speaking. A red microphone icon indicates you are muted. If you are joining via phone, you can also mute and unmute by dialing *6 from your keypad.



2. By default, the main speaker is displayed in the large video window in "Active Speaker Video View." If you would like to change the video layout to see all cameras, click on one of the video layout icons on the top right of the video window.

3. Each session of the conference will be followed by a joint question and answer period for all speakers from a particular session. To ask a question, use the chat function by clicking on the chat bubble button on the bottom of the screen.
   You may need to mouse over or click on the bottom of the WebEx video for the floating button menu to appear. When you write your question, please include the name of the speaker for whom the question is meant. Questions will be read aloud by the co-chair of the session.



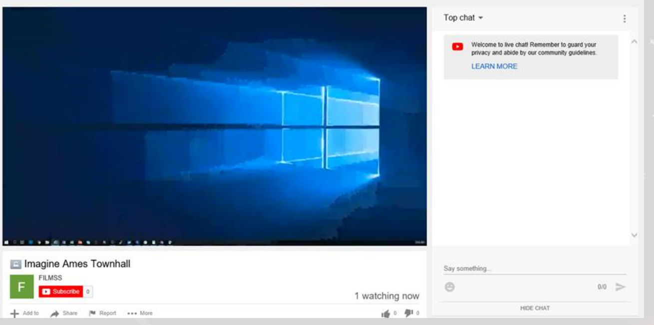
4. For a full description of meeting controls and navigation, see:

WebEx Help: Get Started with Cisco Webex Meetings for Attendees

Joining YouTube

Navigate to the provided YouTube channel

To ask a question during the QA period, type your question into the chat bar on the right side of the screen



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.

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 Master's in Business Administration from Norwich University in Northfield, Vermont.

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 bachelor's from U.C. Berkeley in 1996 and master's 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.

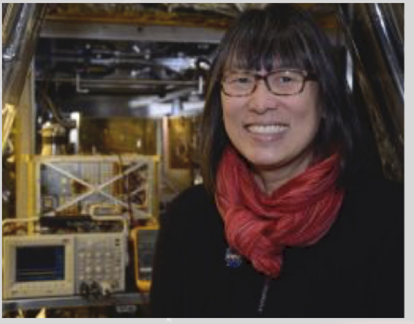
Ryan Nugent is currently a Co-Principal Investigator of the CubeSat Program at Cal Poly in San Luis Obispo, CA. Ryan has spent 12 years with the program, starting as an undergraduate student and continuing as a graduate student in Aerospace Engineering. Ryan took a staff position at Cal Poly in 2011. He has lead development efforts for Cal Poly dispenser designs, developing the processes required to support NASA, The U.S. Department of Defense, European Space Agency, and Commercial Organizations in certifying CubeSats and CubeSat dispensers for domestic and international launches. Overall, Ryan has supported 23 orbital launches in the U.S. and internationally involving over 155 satellites, including the MarCO CubeSats. Ryan is currently managing the CubeSat Program at Cal Poly, which manages the CubeSat Standard and is currently working on additional launch campaigns and supporting the development of 5 different satellite projects at Cal Poly.

Michael Saing is a Systems Engineer in the Project Systems Engineering and Formulation Section at the Jet Propulsion Laboratory (JPL). He develops system model, analysis, and architecture as well as a subject matter expert in space mission cost estimating and analysis. He is also one of the subsystem's engineer chair for JPL's Foundry elite concurrent engineering design team for TeamX, TeamXc, and A-Team. Michael is also tasked by NASA Headquarters particularly focusing on data collection and analysis for small satellites/cubesats and space remote sensing instruments. He graduated with an Aerospace Engineering degree (B.S.) from CSU Long Beach. While working towards completing his academics, he volunteered and worked with a group of mentor engineers and students to gain knowledge and experience in design, build, and launch reusable launch vehicles (RLV) and nanosatellite launch vehicles (NLV) for customers such as DoD and NASA. After graduation, he started his early career work at the NASA Ames Research Center in Mountain View, CA prior to joining JPL. His interests are in the areas of astrophysics and planetary science, remote sensing instruments, and satellite constellation and swarms.

Zsarina Benecken is currently the Technical Group Supervisor of the Mission Interface Coordination Group in the Mission Systems Engineering Section 394. She brings 20 years of experience at JPL spanning all phases of the mission. She was part of the Deep Space Network (DSN) Data System Operations Team (DSOT) where she worked 24x7 real-time operations to ensure data and command delivery through Telemetry, Tracking, and Command legacy software and Space Link Extension (SLE). She has in depth knowledge of the Ground Data System (GDS) by working on the GDS's Integration, Test and Deployment team supporting Spitzer, MER, MSL, JUNO and InSight. Her latest flight project experience was the Integration and Test Lead for InSight which included Verification and Validation of the GDS for all deliveries and managed End to End DSN and ESA station testing. After her significant contribution to InSight's launch and EDL, she joined MGSS as a Ground Data System Engineer and led the effort for Test Data Acquisition and Command (TDAC) AMMOS product. She has held positions of increasing responsibility in GDS for both flight projects and MGSS.

4. Keynote Speaker Biographies

Florence Tan (*NASA Headquarters*)



Florence Tan is the Chair of the Small Spacecraft Coordination Group (SSCG) at NASA Headquarters. She is also the Deputy Chief Technologist (DCT) for NASA's Science Mission Directorate (SMD). In her role as SSCG Chair, she leads the SSCG to coordinate and develop NASA's strategy and vision for small spacecraft in science, exploration missions, and technology activities and provide advice to the Associate Administrators of the Space Technology Mission Directorate (STMD), Human Exploration and Operations Mission Directorate (HEOMD) and SMD. As the DCT for SMD, she supports the SMD Chief Technologist to survey and assess technology needs for NASA's science. Previously, Florence worked at NASA Goddard Space Flight Center (GSFC) for 32 years as a lead electrical engineer, cognizant engineer, designer, integration and test engineer, manager, and operator for NASA spaceflight projects. She has designed, built and launched seven mass spectrometers to destinations including Mars, Saturn, Titan, and the Moon. Florence has received numerous awards including the NASA Medal for Exceptional Achievement, the Robert H. Goddard Exceptional Achievement for Outreach, Goddard Division Excellence Award, multiple NASA Group Achievement Awards including the NASA Honor Award Silver Achievement Medal, Goddard Special Act Awards and Goddard Peer Awards. Florence has made it a personal goal to promote science, technology, engineering and mathematics education, and she actively engages in outreach activities with students and the public to promote NASA science and technology advancements multiple times per year in the last 15 years. Florence holds a B.S. degree in Electrical Engineering from University of Maryland, and an M.S. in Electrical Engineering and MBA in E-Commerce from Johns Hopkins University.

Vlada Stamenkovic
(*Jet Propulsion Laboratory*)

Vlada Stamenkovic is a Research Scientist at the NASA Jet Propulsion Laboratory in the Science Division and CIFAR Fellow. At JPL, he serves two roles: one as a scientist and one as a technology mission developer.

As a scientist, he explores how planets & life co-evolve, with a focus on the hydrology and subsurface energetics that enable life—on the Earth, in our solar system, and beyond. As a technology mission developer at JPL, he is leading the science mission concept development for Mars small spacecraft in the Mars Program and is the PI of the TH2OR instrument development. The latter is a tool that is uniquely capable to detect liquid water in the deep subsurface. For Mars, TH2OR aims to sound for liquid water possibly at depths of many kilometers and help answer the question of whether there could be still life on Mars. Beyond Mars, TH2OR can help detect ores for ISRU on the Moon and on asteroids, and could empower small communities on our own planet to find drinkable water sources—bridging space exploration to sustainability and the commercial sector. He is also founder of the New Mars Underground, a community of scientists and engineers dedicated to exploring the Martian subsurface for signs of life and resources.

Vlada has earned his MSc in Physics at the ETH in Zurich, whilst sending as PI two biophysical instruments to space—one on the Russian space satellite FOTON M-1 and one on the Cervantes mission to the ISS. He completed his PhD in Planetary Sciences with the German Aerospace Center, the University of Münster, and the European Space Agency in 2012. From there on, he crossed the Atlantic to work as a Swiss National Science Foundation Fellow at MIT exploring the habitability of exoplanets, moved as a Simons Collaboration on the Origin of Life Fellow to Caltech to work on Mars habitability and geobiology, and ultimately joined JPL in 2018—aiming to bring revolutionizing science with small spacecraft to Mars & beyond.

5. Conference Abstracts

K.1 NASA Small Spacecraft Strategic Plan and Thinking Beyond Low Earth Orbit

Florence Tan
(*NASA Headquarters*)

For several years, NASA has recognized the potential of small spacecraft to enhance and enable Agency objectives of innovative science and exploration activities. As such, the Science Mission Directorate (SMD), Human Exploration and Operation Mission Directorate (HEOMD), and the Space Technology Mission Directorate (STMD) have cooperated to adopt, develop, and enable a role for small spacecraft for NASA missions. The Small Spacecraft Coordination Group or SSCG was formed to improve coordination among mission directorates. The NASA Small Spacecraft Strategic Plan, released in August 2019, is a document to formalize the overarching integrated strategy for the role small spacecraft within the Agency. It identified four cross cutting themes: High Priority Innovative Science, Support to Human Exploration, Disruptive Technology Innovation, and Regular Access to Space. This work will address the four cross cutting themes in the Small Spacecraft Strategic Plan and outlines the strategies and focus areas to advance these themes.

K.2 Mars Small Spacecraft – the Opportunity of the Roaring 20ties

Vlada Stamenkovic, N.J. Barba, R.C. Woolley, C.D. Edwards, P.E. Clark, L. Giersch, and T.A. Komarek
(*Jet Propulsion Laboratory, California Institute of Technology*)

Mars has still many mysteries that wait to be explored. Fast changing whiffs of methane observed over the last fifteen years, and recently measured seasonal fluctuations of oxygen have puzzled scientist—especially as methane on the Earth is manly produced by life and should, on Mars, not decay within days, as observed, but rather slowly with a half-life of three hundred Earth years. Recent data from the MARSIS orbiting radar have suggested the possible existence of liquid groundwater beneath the South Polar Layered Deposits one mile deep. However, the depth at which the data have been taken is at the verge of MARSIS' sounding capabilities and could have alternative interpretations. In the same time, we have finally discovered small quantities of organic material in Martian rocks with the Curiosity rover, ingredients essential for life, but it is not clear whether, or how, that material was created on Mars or whether it might have been delivered exogenically by meteorites. These discoveries all leave open questions, especially as to whether we might be seeing traces of possibly habitable environments in the Martian subsurface, which to this date has almost not been explored. Could life still be hiding in the Martian deep where groundwater could exist? We do not have the data to judge this.

On the other hand, many processes that occur on Mars—across seismology, climate, atmospheric erosion and many more can only be better understood if we enable 4D monitoring, globally in 3D and across time. This would not just allow us to understand what causes dust storms, quakes or drives water from subsurface to ionosphere, but would also allow us to set monitoring stations for human exploration—emphasizing how big Mars science questions of the future tightly link to human exploration. Small spacecraft, well below half of the Discovery Class budget, either in orbit or on ground, provide the opportunity to address all those questions by

Continued

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(*Jet Propulsion Laboratory, California Institute of Technology*)

(1) performing fundamental new measurements,
(2) executing targeted science objectives with a focused instrument suite,
(3) accessing landing regions which are normally too risky,
(4) enabling 3D (global) and 4D (global and temporally continuous) measurements, and
(5) exploring large-scale areas with sensor-driven mini-scouts.

Objectives of interest include characterizing the atmosphere and ionosphere, including local and regional dust, energetic particles, wind, temperature, pressure and electromagnetic fields on a global scale and across variable heights above the surface; determining with high spatiotemporal resolution current climate and its variability as a function of season, latitude, time of the day and terrain; polar science would be also significantly enabled due to the higher permitted risk to land in polar regions; performing assessment of resource inventories, including ice water and ores; assessing modern-day habitability by localizing the sinks and sources or trace gases, such as methane, by estimating the delivery of organics by meteorites, by constraining shallow subsurface redox profiles, and by especially characterizing deep subsurface liquid groundwater, a possible last modern habitat on Mars. In the following talk, I want to provide insight on the big science opportunities that can be addressed with small spacecraft around Mars, first from a wide perspective, and second by focusing on how small spacecraft below a cost target of $250 M might help us answer one of the biggest questions of planetary exploration "if there is still life on Mars".

Acknowledgments: This work was performed in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Predecisional information for planning and discussion purposes only. The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

A.1 2020 Update for the Lunar Ice Cube Mission

Pamela Clark
(*Jet Propulsion Laboratory, California Institute of Technology*),
Ben Malphrus and Kevin Brown (*Morehead State University*),
Cliff Brambora, Terry Hurford and Jerrod Young
(*NASA Goddard Space Flight Center*)

Overview Lunar Ice Cube, to be launched in 2021, is a deep space cubesat mission with the goals of demonstrating 1) a cubesat-scale instrument capable of addressing NASA HEOMD Strategic Knowledge Gaps related to lunar volatile distribution (abundance, location, and transportation physics of water ice), and 2) cubesat propulsion, via the Busek BIT 3 RF Ion engine. 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, the AIM/IRIS microcryocooler, and, along with several other EM1 cubesats, the JPL IRIS Version 2.1 ranging transceiver and the BCT XACT attitude control system. We will be delivering science data from the broadband IR spectrometer, as described below, to the Planetary Data System.

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 understanding [2,3,4] of the forms and sources of lunar volatiles in spectral, temporal, spa-tial, and geological context as function of time of day and latitude. BIRCHES is a compact version (2 U, 3 kg, 10-20 W) of OVIRS on OSIRIS-REx [5], a point spectrometer with a cryocooled HgCdTe focal plane array for broad-band (1 to 4 micron) measurements. The instrument will achieve sufficient SNR (>100) and spectral resolution (</= 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 AIM microcryocooler/IRIS controller is designed to maintain the detector temperature below 120K. In order to maintain the cold temperature (<220 K) of the optical system (all aluminum construction to minimize varying temperature induced distortion), a special radiator is dedicated to optics alone.

Continued

A.1 2020 Update for the Lunar Ice Cube Mission

Pamela Clark
(*Jet Propulsion Laboratory, California Institute of Technology*),
Ben Malphrus and Kevin Brown (*Morehead State University*),
Cliff Brambora, Terry Hurford and Jerrod Young
(*NASA Goddard Space Flight Center*)

Mission Design Science data-taking with the BIRCHES payload will occur primarily during the science orbit (100 km $\times$ 5000 km, equatorial periapsis, nearly polar), highly elliptical, with a repeating coverage pattern that provides overlapping coverage at different lunations. Between lunar capture and the science orbit, we hope to use sever-al orbits for instrument calibration and capture of spectral signatures for larger portions of the lunar disk, traversing from terminator to terminator. Science orbit data-taking will occur over several months, allowing for sufficient collection of systematic measurements as a function of time of day to allow derivation of volatile cycle models.

Development Status The propulsion system is currently undergong environmental testing and will be delivered to Morehead in mid-March. The onboard computer will have been delivered by then, and testing with flight software, for each subsystem as it is delivered, will begin in mid-March. BIRCHES will complete operational environmental testing and calibration May for delivery in early June. Spacecraft integration will occur throughout the summer of 2020, with final operational environmental testing to be completed early fall.

References:
[1] Clark P.E. et al. (2017) SPIE Proceedings 9978, 99780C, doi:10.1117/12.2238332;
[2] Pieters C. et al. (2009) Science, 326, 568-572;
[3] Sunshine J. et al. (2009) Science, 326, 565-578;
[4] Colaprete A. et al. (2010) Science, 330, 463-468;
[5] Reuter, D. and A. Simon-Miller, (2012) Lunar and Planetary Science, 1074.pdf.

A.2 Near Earth Asteroid Scout Mission – Status Update a Few Weeks Before Delivery!

Julie Castillo-Rogez, Annie Marinan, Jack Lightholder,
Christophe Basset, and Calina Seybold
(*Jet Propulsion Laboratory, California Institute of Technology*),
Les Johnson, Matthew Pruitt, Joseph Matus
(*Marshall Space Flight Center*)

The Near Earth Asteroid Scout (NEAScout) mission was selected in 2013 as one of the 13 CubeSats to be flown on Artemis-1 (formerly Exploration-Mission 1). NEAScout is being developed under NASA's Advanced Exploration Systems. It is a science and technology demonstration mission. NEAScout's science objectives are to retire strategic knowledge gaps for Human exploration of asteroids. It will target and perform a slow flyby of an asteroid during which the spacecraft visible imager will acquire far and close range images of the asteroid with the objectives to constrain its physical and dynamical properties, close environment (e.g., search for companions and debris), and surface properties. NEAScout is propelled by an 86 m^2 solar sail that builds on the 2010 pathfinder NanoSail-D2. This will be the largest solar sail ever to be flown in space. Other technology demonstrations include a small computer called Sphinx and on-board data processing, analysis, and extraction for prioritized downlink. NEAScout will also fly an improved version of the IRIS radio flown on the Mars CubeSat One CubeSats.

At the time of the conference, NEAScout will be nearing full integration and testing before delivery for integration in the dispenser to be mounted on Artemis-1 Multi-Purpose Crew Vehicle stage adapter. This presentation will review the science and technology objectives of NEAScout, the status of integration and testing, and the projected imaging performance at the target.

NEAScout paves the way for future missions that would benefit from low cost, small spacecraft applied for example to networked constellations enabling new class of science or fleets targeting many objects. The Sphinx computer has a performance similar to the RAD750 for a fraction of the resource requirements. The NEAScout solar sail will represent a major milestone in sail technology with far-reaching applications to heliophysics missions, in particular.

Acknowledgments: The NEAScout project is managed by NASA's Marshall Space Flight Center. Part of this work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

A.3 Near Earth Asteroid Scout (NEA Scout) Science Concept of Operations Utilizing Onboard Data Analysis

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As part of the Artemis 1 mission, Near Earth Asteroid Scout (NEA Scout) will fly with twelve other CubeSats to a variety of interplanetary destinations. These small spacecraft rely on the Deep Space Network (DSN) for communication, adding over a dozen new missions to the already heavily subscribed resource. DSN time allocations will be particularly taxed during the shared initial spacecraft deployment phase and critical mission phases for each spacecraft. This resource constraint, coupled with the physical limitations of small spacecraft, create new challenges for doing science on a CubeSat platform. NEA Scout will travel nearly 1 AU to an asteroid which, due to its size and albedo, has not had its orbit fully characterized from Earth. From 60,000 km the team will need to identify the target, plan course correction maneuvers, use optical navigation to navigate to the target and acquire science images during a flyby of the target. These tasks must all be accomplished with data rates of ¡1 kbps. We present a strategy for utilizing onboard image calibration, shift detection, noise reduction, data compression and scene value estimation to meet the operational constraints posed to the NEA Scout operations team. As part of the verification, validation and operations preparation, data from New Horizons, Rosetta and terrestrial tests have been used to validate the flight software and prepare the science team for conducting science in this low bandwidth and limited spacecraft contact environment. We will present an overview of the algorithms, test strategy, instrument calibration and planned concept of operations for NEA Scout, which cumulatively will enable scientific data collection, summarization and transmission to Earth.

Acknowledgements: The NEAScout project is managed by NASA's Marshall Space Flight Center. Part of this work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

A.4 Lunar Flashlight Mission Overview

Daniel Grebow, Stefano Campagnola, Robert Haw, Theodore Sweetser
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Lunar Flashlight (LF) is one of several CubeSat missions planned as secondary payloads to the Orion multi-purpose crew vehicle for the Artemis 1 mission. The launch, anticipated no earlier than Summer 2021, will be the first launch of the Space Launch System, and will send the uncrewed Orion spacecraft and CubeSats to the Moon. The LF spacecraft will use small maneuvers and lunar flybys to achieve an eight-month journey to a lunar near-rectilinear halo orbit (NRHO) with an orbital period of approximately 5.9 days and perilune altitude 15 km over the south pole region. The LF NRHO is a member of the Earth-Moon northern halo orbit family, as distinct from the Lunar Gateway NRHO that is planned for the southern halo orbit family. In the NRHO LF will determine the presence and abundance of water ice in cold traps on the surface near the lunar south pole by shining lasers into shaded polar regions and measuring surface reflection at four different wavelengths within the shortwave infrared region. The orbit provides ten 1-2 km swaths across the south pole region, $>$10% of the time over permanently shadowed areas, in the 60-day duration of the baseline science phase. The relatively small lunar orbit insertion maneuver and minimal $\Delta - v$ to maintain perilune to 10-20 km above the lunar surface make the NRHO a feasible science orbit for this mission.

In this paper we describe briefly the science goals and the spacecraft architecture. The mission design and navigation analyses for LF are also discussed in detail. Although currently the exact launch date is to be determined, we have designed a reference mission assuming an August 14, 2021 launch. We provide a detailed concept of operations for deployment leading into the first lunar flyby and for the short period around each perilune in the science orbit. This concept of operations includes trajectory correction maneuvers for the transfer to the lunar science orbit and orbit maintenance maneuvers in the NRHO. Our method for designing the cruise transfer is summarized, including sensitivities of the delta-v, eclipse durations, and time of flight to different launch times within a daily launch window and to different launch dates. We describe how the NRHO is designed and perilune maintained to 10-20 km altitude, and perform coverage analyses verifying that the orbit will satisfy the mission science requirements. The total delta-v for the mission, including perilune maintenance, is less than 135 m/s.

A.5 LunaH-Map Mission Technologies and Developments

Igor Lazbin, Craig Hardgrove, Jim Bell, Richard Starr, Anthony Colaprete, Darrell Drake, Igor Lazbin, Erik Johnson, James Christian, Lena Heffern, Anthony Genova, David Dunham, Bobby Williams, Derek Nelson, Nathaniel Struebel, Alessandra Babuscia, Paul Scowen

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.

A number of technology developments are employed to enable this unique mission. Miniature neutron spectrometer (Mini-NS), with sensitivities capable of identifying small-scale ($< 15km^2$) regions of hydrogen enrichments on the order of 600ppm +/- 120ppm is a perfect payload to be hosted on a cubesat platform. It is low power, and does not require precision pointing. In order to achieve desired mission orbit with 10 to 15 km perilune above the South pole of the Moon, electric propulsion and a deployable articulated solar array are used. Communication with Earth will be achieved via the Iris radio, similar to that used on the MarCO spacecraft, albeit with a lower power output. A custom low mass structure is especially suited for housing all spacecraft components, maximizes radiator area, and accommodates the spacecraft harness. Mission-unique spacecraft software modules were also developed for this mission in order to minimize burn pointing errors and to unload reaction wheel momentum using the electric propulsion system.

A.6 VIPER – Volatiles Investigating Polar Exploration Rover: Mission Overview

Ryan Vaughan
(*NASA Ames Research Center*)

VIPER is a low cost, lunar volatiles detection and measurement mission that will be delivered to the lunar south pole by one of NASA's Commercial Lunar Payload Services partners and will characterize the nature of the volatiles in the area and extrapolate this data to create global lunar water resource maps. It will be the first mining expedition on another world while simultaneously addressing fundamental planetary science questions. Prospecting for lunar water at the poles is the next step in understanding the resource potential and addressing key theories about water emplacement and retention. It now appears that potentially economically significant amounts of water ice exists at the poles of the Moon, however, the distribution of this water is still not under-stood at a level sufficient to fully evaluate economic models. The water ice (and other potential volatiles), the "ore body", needs to be understood at the scales of 10s to 100s of meters to evaluate localization, extraction and processing techniques.

To accomplish this, VIPER will survey permanently-shadowed regions, semi-permanent shadowed regions, and even semi and full sunlit areas in order to have a comprehensive survey of polar region volatiles, to best inform future mission architectures. In order to characterize the volatiles, a payload suite consisting of a neutron spectrometer, mass spectrometer, near infrared spectrometer and a 1-meter drill will be hosted on the VIPER mobile lunar rover platform. Since VIPER is a relatively low cost, schedule-constrained, risk-tolerant mission, there are architectural limitations that require unique mission planning constraints to enable exploration of the lunar south pole region. These regions offer unique challenges such as uncertain terrain conditions, rock and crater hazards, lunar dust, multipath communications effects, extreme thermal environments and multiple over-lapping planning constraints. Mission design/traverse planning, system design capabilities and mission operations are all highly linked through initial development phases. We will describe the current mission overview and the unique approaches taken by the VIPER project based on our programmatic framework and unique mission environment.

A.7 Mars Helicopter Technology Demonstration

Courtney Duncan
(*Jet Propulsion Laboratory, California Institute of Technology*)

The Mars Helicopter Technology Demonstration is now in final preparation for launch to Mars with JPL's Mars 2020 Rover in July 2020. The helicopter plans to execute the first heavier-than-air flight on another planet in April-May 2021. This presentation will overview the helicopter mission and requirements; the design and special circumstances of flight in the thin, cold air of Mars; and some of the commercial off the shelf technologies used.

B.1 Deep Space Station 17: A University-Operated Affiliated Node on the NASA Deep Space Network Providing Telemetry, Tracking and Command Services for Interplanetary SmallSat Missions

Benjamin Malphrus and Jeff Kruth
(*Morehead State University*),
Tim Pham and Jay Wyatt
(*Jet Propulsion Laboratory, California Institute of Technology*)

A new era of Solar System exploration began in 2018 with the launch of the twin Mars Cube One (MarCO) CubeSats. CubeSats are being planned for interplanetary research, with 13 CubeSats slated to fly on NASA's Artemis 1 mission in 2020. The success of MarCO and Artemis 1 will no doubt open the door for CubeSat and smallsat exploration of the solar system. All of these activities will require ground support for communications, navigation and tracking-support that equires significant infrastructure including ground stations with large apertures, full-motion antennas and specialized deep space ranging and telecommunication instrumentation. The DSN, even with the expansion of the new antennas planned, and with the implementation of new techniques (i.e. multiple spacecraft per aperture), will be challenged to accommodate a large number of missions expected as the smallsat revolution unfolds.

To begin to address this challenge, partnership between JPL and Morehead State University (Kentucky, U.S.A.) was initiated in 2014 to develop a strategy to enhance DSN capabilities by utilizing existing non-NASA assets (i.e. university and non-profit radio astronomy observatories). An enhanced DSN can be achieved by transferring DSN processes and techniques, precision timing standards, data formatting, handling and transfer protocol, and mission and ground operation processes to existing university-based large aperture antennas. The team is using the Morehead State University 21 m Space Tracking Antenna as a case-study to prove the validity of the concept of adding non-NASA nodes to the DSN. The goal of this project is to develop and implement a strategy to enable the integration of MSU 21 m antenna system into the DSN as an auxiliary station to support smallsat missions.

This program will serve as a test-case to define a path for other non-NASA ground stations to provide auxiliary deep space navigation and tracking support for small-sat missions. The program is focused on the implementation of DSN capabilities, techniques and processes, CCSDS data standardization such as Space Link Extension (SLE) protocol, tracking techniques and capabilities, and asset scheduling capabilities. The 21 m antenna system hardware has been upgraded toward DSN-compatibility and the station, designated DSS-17, is expected to become operational in the Fall of 2020. This talk will provide an overview of the DSS-17 architecture and the plan for performance testing toward Operational Readiness Review.

B.2 Iris Deep-Space Transponder for Artemis Payloads

Mazen Shihabi, Zaid Towfic, Brandon Burgett,
Sarah Holmes, and Matthew Chase
(*Jet Propulsion Laboratory, California Institute of Technology*),
Dana Sorenson (*Space Dynamics Lab*)

In 2013, the Jet Propulsion Laboratory (JPL) developed the Iris Deep Space transponder, a CubeSat compatible software-defined radio (SDR), intended to support the first CubeSat deep space mission: the Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE). The Iris Transponder is a reconfigurable SDR designed for missions requiring interoperability with NASA's Deep Space Network (DSN) on X-band frequencies (7.2 GHz uplink, 8.4 GHz downlink). The transponder provides radiometric tracking support with the DSN to provide navigation products for precise orbit determination while performing standard uplink and downlink communications in a CubeSat/SmallSat-applicable package size.

In 2015, JPL developed the second version of the Iris transponder to be used on the Mars Cube One (MarCO) mission. The second version has, in addition to X-Band transmit and receive functionality, the capability to receive in the UHF band. On MarCO, Iris successfully performed bent-pipe relay direct-to-Earth during entry, descent, and landing (EDL) of the InSight lander, providing the first confirmation of successful landing, including relay of InSight's first image from the surface of Mars.

JPL, in partnership with Utah State University Space Dynamics Lab (SDL) continues to improve and enhance Iris. The latest version of Iris (2.1) is slated to be the main transponder on each of seven secondary payload CubeSat missions of the upcoming Space Launch System Artemis-1 Mission. In this version, several updates to Iris were made. The power supply board (PSB) was redesigned to increase the radiation tolerance, and further miniaturization was performed to reduce the overall SwaP (Size, Weight, and Power) of the unit. In addition, two enhanced navigation and ranging techniques were added: Pseudo-random Noise (PN) Delta-Difference-of-Ranging (DDOR) technique and PN Regenerative Ranging. Also, Over-the-Air Update (OTAU) capability of the Iris firmware/software was added. The last feature will allow future mission to make updates to Iris's firmware and software in flight, if needed.

This presentation focuses on the recent updates that were made to Iris and presents some results from recent compatibility testing at the DSN Test Facility (DTF-21).

B.3 An Inter Planetary Network Enabled by SmallSats and Optical Communications

Jose E. Velazco
(*Jet Propulsion Laboratory, California Institute of Technology*)

This paper describes the implementation of the inter planetary network (IPN) - a large sensor and communications platform along the solar system. The proposed IPN consists of thousands of small spacecraft (e.g. CubeSats) strategically deployed around planetary bodies in the solar system, where each spacecraft is furnished with fast communications and sensor systems. The IPN concept is being proposed as an advanced science and communications platform that could allow for continuous fast communications and remarkable science returns. The IPN spacecraft, furnished with suitable miniaturized sensors, could form an amazing deep space platform for unique observation of the solar system, stars, galaxies and universe. A key feature of the IPN architecture is the use of swarms of spacecraft as network units. High-speed intra-swarm communications could be achieved via omnidirectional optical links. The swarms act as autonomous network nodes and are capable of forming large synthetic apertures that enable high data rate communications among the IPN nodes. Depending on the sensors they carry, these swarms may also be capable of forming large synthetic sensors by rapidly combining data among the spacecraft using optical crosslinks. We envision distances between spacecraft forming a swarm to be in the range of 1E2-1E4 kilometers, whereas distances of 1E6-1E8 kilometers among swarms (IPN nodes) are expected. We provide an example of an initial cislunar IPN implementation where a large swarm of spacecraft is deployed in a lunar L2 halo orbit to form a giant radio telescope to detect potentially habitable exoplanets.

B.4 Comparing Radio Occultation Results from MarCO with Mars Reconnaissance Orbiter and MAVEN: Achievable Radio Science with a CubeSat

Dustin Buccino, Oscar Yang, Kamal Oudrhiri, Norman Lay, and Daniel Kahan
(*Jet Propulsion Laboratory, California Institute of Technology*),
Paul Withers
(*Boston University*)

The twin Mars Cube One (MarCO) cubesats were launched alongside the InSight lander on May 5, 2018 marking the first interplanetary cubesat mission. MarCO-A and MarCO-B were designed as a real-time communications relay demonstration for InSight during the Entry, Descent, and Landing (EDL) phase on November 26, 2018. After InSight successfully landed on the surface of Mars and the MarCO cubesats completed their data relay mission, they continued on a flyby trajectory of Mars. MarCO-A was in a favorable geometry to execute a radio occultation of the atmosphere and ionosphere of Mars, marking the first ever attempt at science data acquisition by a cubesat at another planet. In this work, we compare the results of the MarCO-A radio occultation with those acquired by the Mars Reconnaissance Orbiter (MRO) and MAVEN spacecraft. Although the MarCO-A radio occultation was unable to retrieve temperature/pressure or ionospheric electron density profiles of the Martian atmosphere due to less-than-favorable spacecraft pointing and sequencing, the noise floor during the experiment proved the neutral atmosphere and ionosphere could have been detected. The noise budget and occultation results between MRO, MAVEN, and MarCO show comparable performance, proving small satellites are able to perform radio science experiments to probe the atmospheres and ionospheres of planetary bodies.

B.5 Validating the Optimization of Mission Operations for the Lunar IceCube Mission Using Delay-Tolerant Networking

Nathaniel Richard, Scott Burleigh and Leigh Torgerson
(*Jet Propulsion Laboratory, California Institute of Technology*),
Sean McNeil, Nathan Fite and Chloe Hart
(*Morehead State University*)

The launch of the Artemis 1 mission will likely lead to the influx of deep space CubeSats. It will also launch one of the first university led deep space CubeSat missions. Universities are always looking to minimize flight operations cost; delay-tolerant networking (DTN) is a potential method to optimize mission operations as a way to reduce costs. The Jet Propulsion Laboratory has partnered with Morehead State University to investigate this as part of their Lunar IceCube (LIC) mission. Our presentation will outline the benefits of using DTN, lay out the work we have done so far to prepare the mission to utilize DTN, and describe the in-space DTN experiment. One method of optimizing mission operations is through the automation of data management. The bundle protocol (BP) is part of a suite of protocols that make up DTN. Part of BP is the ability to transfer custody from one node on a DTN network to another. The acknowledgments within the custody transfer can be used by the flight software to automatically delete acknowledged data and free up storage space for new science data. In addition, acknowledgments can be aggregated using the BP aggregate custody signaling (ACS) to minimize the amount of forward traffic to the spacecraft.

The other method that will be explored is the ability for built-in networking capabilities to streamline mission operations by seamlessly extending the spacecraft link to different operation locations. BP functions as an overlay protocol allowing the protocol to transfer data independent of the underlying network protocols. This allows data to go directly from the spacecraft to the engineering or science teams seamlessly. An end-to-end demonstration of the prototype system was performed successfully in late 2019. The demonstration utilized LIC's flight radio (a JPL-developed Iris 2.1) and its ground station hardware. In our presentation we will discuss the status of our upcoming demonstration of a flight-like configuration. This demo will lay the ground work for the first in-space demonstration of DTN on a deep space CubeSat. It will be a full end-to-end test including the flight vehicle and mission operations software. A final in-space experiment will be performed approximately three to four months after launch, during LIC's extended cruise phase. Through this in-space experiment we believe we can show DTN can play an integral part in helping not just deep space mission optimize operations, but all spacecraft missions.

B.6 Loop antenna on a tree for satellite reception

Thomas Choi and Alessandra Babuscia
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Ingie Baho
(*New York University Abu Dhabi*)

Trees can be used as ground station antennas to support long-lasting satellite missions as long as decades or even centuries for travelling solar system and beyond. However, using electromagnetic waves for water dominated trees is very challenging. In this presentation, design of a loop antenna which can fit into a tree branch will be explained as well as the effects of tree on the antenna. Simulated results will also be compared with experimental results.

B.7 Cubesat Constellation Architecture to Support Space-based Property Claims

Jacob A. J. Irwin, J.L. Galache and Eric D. Ward
(*Berkelyn*)

To accelerate low-cost access to extraterrestrial ownership and usage rights, we present a system for providing big data collection and distribution to support the needs of public and private actors' access to space-based property appropriations. Accessible interfaces that serve to streamline the functionalities necessary to support independent claims on property, which is currently a missing essential layer preventing humanity's expedited progress in space exploration and development of an in-space economy. The proposed system integrates software and hardware—a closed-loop management and control system—that codifies in-space activities attributes and may lend to a novel protocol standardization heuristic for asserting and reinforcing independent claims for ownership of celestial matter and rights for performing activities in pre-designated regions of space.

The proposed system software provides a streamlined process through which timestamped transmissions may be decrypted, encrypted, handles, and stored; global positioning system (GPS) information may be accurately calculated and recorded; secure communications capabilities for transmissions throughout the constellation network and with third-party communications services providers; mission-ready software for tracking and navigation; and qualification documentation generation for validating ownership claims (to be further evaluation by authoritative agencies, such as international governing and sovereign nation-state level regulatory bodies).

The proposed system hardware is comprised of such integral components both typical of a traditional satellite network mission and, also, specific to the requirements of the newly proposed picosatellite constellation: CubeSat construction materials; mission-defined picosatellite-mounted sensors and instrumentation; solar arrays; gyroscopes; miniature ion thrusters; and antennae. The physical satellite hardware consists of lightweight sensors aboard picosatellite chassis (each between 0.25U and .5U in size) housed within a larger CubeSat locker (between 4U and 6U in size). Each picosat is individually deployable from its parent housing, the nanosatellite-sized lockers. Once the parent nanosatellite reaches its mission-defined position in geostationary transfer orbit (GTO), individual picosatellites are precisely deployed to rendezvous with (reach orbit or land on) strategically pre-selected natural small bodies. The proposed system works with external larger scale interplanetary and/or interstellar communications networks, offloading higher-level tasks. Future advancements for this system's technology are also explored, including improvements in secure communication using quantum key distribution and modularity in the CubeSat design and construction for instrumentation extensionality for: local (interplanetary) data collection with miniature lightweight X-ray optics, such as composition analysis with X-ray fluorescence imaging); and deep space (interstellar) navigation with X-ray pulsar-based timing.

C.1 Rocket Lab Electron and Photon-Enabled Beyond LEO Missions

Richard T French
(*Rocket Lab USA*)

Rocket Lab, the world's leading dedicated small satellite launch provider, recently announced the next evolution of its mission services: the Photon small spacecraft platform. Photon evolves Electron's heritage third stage, also known as the Kick Stage, by incorporating high power generation, high-accuracy attitude determination and control, and radiation-tolerant avionics to provide a bundled launch-plus-small satellite offering.

Photon is a family of small spacecraft with a common bus architecture to accommodate a variety of payloads and instruments without significant redesign. Rocket Lab provides dedicated launch of Photon integrated with ESPA-class payloads as an alternative to rideshare. Dedicated launch offers better performance, targeting the exact orbit required to deliver the best capability when the payload is ready. Photon eliminates the parasitic mass of deployed spacecraft buses, allowing for full utilization of Electron's lift capacity and usable volume by the instrument or payload.

Photon leverages numerous components that have significant flight heritage, including the storable Curie bi-propellant propulsion system. In addition to the ten successful orbital flights of the Kick Stage, over 1,650 Curie propulsion ground tests have been conducted. New subsystems, including power management avionics, high performance compute, and attitude control assemblies are being developed in-house and will soon have flight heritage.

A high delta-V variant of Photon is enabled with a higher performance version of the Curie propulsion system, larger propellant tanks, and a precision orbit determination system.

In Rocket Lab's beyond-LEO mission concept, Electron delivers the high delta-V variant of Photon, integrated with payload, to a circular parking orbit before a series of burns, or phasing maneuvers, establish increasingly elliptical orbits. Each phasing maneuver is followed by a designed number of phasing orbits at the new apogee altitude before the next maneuver is performed. After the nominal phasing maneuvers are performed, a final burn places Photon on an escape trajectory. The phasing orbit approach enables a precise alignment to mission-specific right ascension of the ascending node and argument of perigee. Photon can continue to fly with the payload, or the payload can be deployed to take advantage of further staging. The typical operational lifetime from launch until escape is four to eight days.

With a high delta-V variant of Photon, this mission architecture enables precise targeting for small spacecraft missions beyond LEO with instrument/payload masses up to 50 kg without the need for a medium or heavy lift launch vehicle, greatly expanding the potential for planetary exploration.

C.3 Lessons learned from the first build of Phase Four's Maxwell engine

Michael Kwapisz, Grant Dunaway, Austin Prater,
Jason Wallace, and M. Umair Siddiqui
(*Phase Four*)

Thousands of small satellites are expected to be launched over the next decade. Electric propulsion is critical to these missions, enabling orbit raising and maintenance, as well as collision avoidance and safe deorbiting capabilities. Historically, complex, expensive propulsion systems have hindered the mass production and mass deployment of large constellations of small satellites. Phase Four designs and manufactures Maxwell, a xenon-based radiofrequency (RF) plasma engine that is smaller, lighter, and more cost-effective than these legacy systems, without compromising on performance. Maxwell generates thrust by applying RF power to create plasma from xenon propellant, and accelerating that plasma out of your spacecraft.

In this talk, we'll share design decisions and lessons learned from the first build of Phase Four's Maxwell engine for small satellites.

C.4 LauncherOne

Brian Hirsch
(*Virgin Orbit*)

The first two decades of CubeSat development have almost exclusively focused on Low Earth Orbit (LEO) capabilities. However, as the JPL MarCO CubeSat demonstrated, the small satellite revolution is rapidly deploying technology enabling CubeSat missions to beyond Low Earth Orbit (LEO), including to the Moon, Mars, and beyond. The advent of this new class of spacecraft has created an opportunity within the small launch industry to provide low cost, dedicated launches to increase access beyond LEO to CubeSat developers.

The initial capabilities for Virgin Orbit's LauncherOne launch vehicle were tailored for Low Earth Orbit. However, the LauncherOne system can be readily modified with a highly energetic upper stage to offer small satellites launch opportunities to the Moon, Mars, and other celestial bodies. This new capability will expand access beyond LEO to small satellite and CubeSat developers, access that has previously been reserved for larger, more traditional spacecraft. By increasing the supply of deep space launch options, Virgin Orbit hopes to foster increased CubeSat innovation and science-gathering capabilities.

C.5 An Accessible CubeSat Hall Effect Thruster for Interplanetary Missions

Colin Warn and Dan Lev
(*Washington State University*)

A low-cost, CubeSat flight-ready Hall Effect Thruster, power system, and propellant feed-system can be built by a small engineering team into a 1U-sized bus for $10k. Western Michigan University has demonstrated that a low-cost, laboratory-ready Hall Effect Thruster can be built at a fraction of the cost compared to current market offerings and open designs. Cal Poly has demonstrated that a low-cost electrothermal propulsion system can be integrated into a 1U CubeSat. The Hall Effect Thruster technology, if integrated into a CubeSat form factor, would enable CubeSats to perform low-thrust interplanetary missions: Such as a cislunar transfer as demonstrated by missions such as Smart-I. One such repercussion would be the ability for payloads to be sent from a low Earth orbit to a lunar orbit in a low-cost CubeSat bus.

C.6 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: N2; N9; and N36 LUNA; and IOS' Personal Satellite Kits will fill those needs.

After a decade of RD, the NEPTUNE 2 (N2) is undergoing its final suborbital flight tests and orbital launch licensing. The N2 is designed to launch a 30-kg small-sat payload(s) to LEO for under $1 million. Interorbital's orbital launch manifest now numbers 160+ picosats. Orbital launch services are set to begin in Q3, 2020, followed by a 2021 Moon impactor mission, Lunar Bullet, with Ed Belbruno's Innovative Orbital Design.

A 2020 suborbital launch of the NEPTUNE CPM 2.0 will test IOS' guidance and control systems and provide a platform for flight-testing significant science applications and breakthrough technologies like the Wayfinder II, a 3U CubeSat and hosted–payload platform designed and integrated by Boreal Space, NASA Ames Research Park. It carries a mission called SHRINE.

SHRINE stands for the Stanford, Hakuto, Raymix, Inventor, NUS Experiment. Five separate organizations provided payloads for integration into the Wayfinder spacecraft bus. The Extreme Environments Lab at Stanford University supplied a Gallium-Nitride-based magnetic-field instrumentation payload. Japan's Team Hakuto (now iSpace), provided a robotics experiment to validate their hardware and software assembly. The National University of Singapore contributed a materials experiment to research potential changes to a graphene sample when subjected to launch loads. Space Inventor of Aalborg, Denmark supplied their SpaceLink UHF radios for which they seek TRL advancement. Finally, the popular Latin American artist Raymix contributed a musical piece for downlink from the SpaceLink radios. This launch's flight data will complement payload performance data, allowing participating teams to iterate and improve designs, and raise Technology Readiness Level (TRL) for future missions.

C.7 FEEP electric propulsion systems for small satellites

David Krejci and Alexander Reissner
(*ENPULSION*)

The IFM thruster technology is a fully integrated electric propulsion subsystem, including thruster head, propellant tank and feed system, and power electronics. Using a solid metal propellant, this technology achieves highest total impulse per volume.

Building on the long heritage of liquid metal ion sources developed by FOTEC and flown on several ESA and NASA missions, the ENPULSION IFM Thruster FEEP family has been successfully introduced into the commercial market. Standardization, modularity, simple integration due to solid and unpressurized propellant, together with high rate production allows for flexible propulsion solutions adapting to different spacecraft classes at low cost.

The IFM technology is based on liquid metal Field Emission Electric Propulsion (FEEP) principle, producing thrust by electrostatically accelerating previously extracted and ionized propellant to high exhaust velocity. The IFM Nano Thruster is a standalone propulsion solution for Nanosatellites, or as clusters for small spacecrafts, allowing for additional attitude control. The thruster can be operated between 10 and 40 W input power including neutralizer, resulting in thrust of up to 0.35mN and fits into less than a standard Cubesat unit. By varying extraction potentials, the thruster can be operated at specific impulse levels between 2000s and 6000s, adapting to mission needs as well as power availability. Due to the high specific impulse and high propellant density, the thruster can produce total impulses of 5000 Ns when operated at specific impulses at 2000s and 5000s respectively.

The IFM Micro Thruster is a 3.2kg thruster including up to 1.7kg of propellant, which can be operated at thrusts up to 1.5mN and up to 100W. The thruster is designed to be panel mounted, and can be operated at different thrust levels as well. At time of writing, the thruster has passed CDR and first qualification models have been built.

At time of writing, 28 IFM Nano Thruster have been launched on spacecraft ranging from several kilograms to over 150 kilograms. Based on the same emitter technology, the IFM Micro Thruster has been developed, which operates 4 IFM emitters in parallel and can provide unmatched total impulse density. This work provides an overview of the current status of FEEP propulsion systems, presents in-orbit data of IFM Nano Thrusters and first testing results of the IFM Micro Thruster.

D.1 A 200 Year CubeSat That Sings With Trees

Steve Matousek, Alessandra Babuscia, Anthony Freeman,
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(*Jet Propulsion Laboratory, California Institute of Technology*),
Julia Christensen (*Oberlin College*)

During the coming decades of robotic space exploration it is very likely that humans will be able to send a probe on an interstellar mission to a nearby solar system. To accomplish this feat, it will be necessary to learn how to reliably make small space systems that last for decades. One way to make near-term progress is to build and launch one or more CubeSats that are designed to last 200 years. The 200-year CubeSat is part of a system designed to merge science, engineering, design, and art. The 200 year CubeSat could communicate with trees properly equipped with sensors and an antenna. Trees routinely live over 200 years. Tree measurements recorded over long periods of time tell a story. If sonified, the tree measurements sound like a song. The CubeSat environment in Earth orbit can also be measured and sonified. Transmitted back-and-forth between the tree and CubeSat, this song is a demonstration of the type of longevity, design, and creativity required for an interstellar probe mission.

200 Year CubeSat: For a CubeSat to last 200 years several basic principles hold.

1) Keep the CubeSat as simple as possible.

2) Operate the CubeSat as little as possible per day while still maintaining periodic contact with one or more trees.

3) Maximize the outer surface area and minimize the mass.

4) Keep the CubeSat as simple as possible. Simple systems have less ways to fail. Eliminating attitude control and propulsion means those subsystems won't fail. If the greater external surface area is populated by more solar cells than needed, than the CubeSat can tolerate 35% - 50% degradation over 200 years. Operation only while in sunlight means no batteries are required. Placing the CubeSat in a 1000 km altitude orbit ensures that both radiation and drag are minimized. A low power UHF telecommunications subsystem communicates with the tree. Command and data handling are accomplished by one or two on-board simple processors that operate as little as possible. As little as one hour of operation every 24 hours seems feasible. Thermal control is passive with large surface areas.

5) Operate the CubeSat as little as possible per day while still maintaining periodic contact with one or more trees. From the 1000 km altitude orbit the CubeSat passes over one or more trees per day. Simple timing or "ping" based operations give sufficient communication opportunities while keeping the operating time to a minimum. Thick aluminum shielding minimizes electronics radiation exposure. Note that a 2 to 3 year accelerated ground test could prove out the concept and aid the design process for the flight of a 200-year CubeSat.

6) Maximize the outer surface area and minimize the mass. Unlike most CubeSats, the 200-year CubeSat has a large "cube," likely at least 1 m3, populated only with 2 – 3 U of simple redundant electronics. This low mass to surface area keeps things simple and helps design for longevity.

The 200 Year CubeSat could be designed and flown within a few years. This part of the tree – CubeSat communication "song" is a step towards the larger goal of an interstellar probe. The 200-year CubeSat can and should be launched. Learning how to create longevity while exercising science, engineering, design, and art will yield benefits beyond what any of us can imagine.

D.2 The Tree of Life: A 200-Year CubeSat

Julia Christensen
(*Oberlin College*)

The Tree of Life grew out of a running dialog between artist Julia Christensen, and scientists and engineers at the Jet Propulsion Lab's Innovation Foundry. The group was investigating the possibilities of building long-lived operational CubeSats. The longevity of technology is one of the most critical—and yet, elusive—challenges of initiating a long-term mission, including an interplanetary or interstellar mission. The Tree of Life mission concept consists of a CubeSat specifically designed to operate in low-Earth orbit for 200 years, transcending contemporary cycles of technological obsolescence. The CubeSat will transmit data about its operational conditions to Earth. The Tree of Life team will augment a set of trees around the planet to act as living terrestrial antennae by harnessing the dielectric properties of the live trees. The team is selecting trees expected to live for 200 years—again, well beyond the short cycles of technological obsolescence prevalent in the 21st century. Sensors on the trees will collect a 200-year data set about their "operational conditions" as well: the trees' response to water, light, their ecosystem, and surrounding climate. The data sent to and from the trees and CubeSat will be translated to sonic frequencies, via custom data sonification software, so that ultimately, the trees and the CubeSat will sing to each other for 200 years.

The Tree of Life concept is designed to address questions of longevity and technologic obsolescence in aerospace design. As The Tree of Life unfolds, so will a song that tells a story about changes in life on Earth, and our technology in space—the song inherently tells a story about human life, as well.

D.3 SmallSat Reactive Flyby to Oort Cloud Comets and Interstellar Objects

Benjamin Donitz
(*Jet Propulsion Laboratory, California Institute of Technology*)

Oort Cloud Comets (OCC) are pristine objects from the edge of the protoplanetary disk. Their exploration opportunities would provide unique insight into the formation of our solar system. About once per decade, a large (10s km) OCC passes into the inner-solar system, which makes it potentially reachable with small spacecraft. Assessing the chemical make-up of these objects via Earth-based telescopic observations remains limited. A flyby mission utilizing small spacecraft with a carefully designed payload suite would enable observation of these OCC and their volatile and refractory material up close.

OCC flybys were previously presumed to be impossible or unaffordable due to the unpredictable occurrence and orbits of these bodies. Moreover, the short lead time between detection and encounter of these bodies would require a reactive mission with a large launch vehicle. Recently, due to the convergence of increased capabilities to discover OCC years ahead of their perihelia, and advancing SmallSat capabilities, a reactive mission to an OCC is now becoming achievable.

A recent study at JPL determined that OCC C/2017 K2 could be encountered by two SmallSats launched in February 2022 for a high-speed encounter of the OCC in August 2022. The same capabilities that would enable fast-response to visit OCC could also be applied to Interstellar Objects (ISO) that are passing through the inner-solar system like Oumuamua or Borisov.

The technical capabilities required to achieve an OCC and ISO flyby exist today. Shorter development schedules as demonstrated by MarCO (Mars Cube One); emerging small payloads (e.g., visible imagery, volatile isotopes, and mineralogy mappers); maturing SmallSat deep space propulsive capabilities; and increasingly capable on-board computing resources to process science data - all make it possible to return meaningful science from an OCC or ISO flyby. However, the programmatic elements required to launch a reactive mission are not in place. NASA's current competitive planetary proposal solicitations follow a prescribed cadence that precludes rapid response following an OCC discovery.

We present the results of a reactive mission concept study on the C/2017 K2 OCC that demonstrates the readiness of technical capabilities and highlight the programmatic shortfall in this category of rapid response mission architectures. As SmallSat technologies and instrumentation continue to improve, the opportunity to explore OCC and ISO using SmallSats is within our reach.

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

D.4 Aerial Reconnaissance of Canyons and Craters on Mars Using Sailplanes

Adrien Bouskela, Tristan Schuler, Sergey Shkarayev, Jekan Thangavelautham (*University of Arizona*), Alexandre Kling
(*NASA Ames Research Center*)

In this work, we propose the deployment of small, low-cost sailplanes in the Martian atmosphere for (1) Imaging of high-priority geological targets located on canyons and cliff walls, (2) Characterizing of the vertical and horizontal winds on Mars, (3) Measuring temperature variations and concentration of trace gases (including water vapor and methane). The proposed sailplane concepts are packaged into CubeSats form-factor, deployed as secondary payloads in orbit or occupying what would otherwise be tungsten ballasts on a flagship mission. These sailplanes will be deployed at high-altitudes and glide to the areas of interest, where they perform continuous reconnaissance, obtaining images from multiple viewpoints and altitudes.

Sizing of the sailplane is based on the low-Reynolds number airfoils and blended-wing-body configuration. To extend capabilities in areas or times of unfavorable wind conditions, an auxiliary propulsion unit is added in the form of a small motor driving a three-blade, retractable propeller. The propeller unfolds when additional energy is needed. In times, where wind conditions exceed the minimum requirements, the propulsion unit extracts the energy from soaring cycle to recharge the on-board batteries.

In the present study, flights over Valles Marineris and Jerezo crater have been simulated by exploiting atmospheric features such as slope and thermal updrafts for static soaring, as well as wind shears and gradients for dynamic soaring. Flight dynamics is simulated using a three degrees of freedom model and the Mars Regional Atmospheric Modeling System (MRAMS).

Our simulations suggest that sustained exploration with minimal to no propulsion is possible while loitering or flying along canyon ridges. After reaching the floor of a canyon for close-up scientific observations, kinetic energy accumulated during the dive and slope lift on the windward side of the canyon are used to re-gain altitude, minimizing the need for propulsion-aided climb. The leeward sides of the canyon present shear layers favorable to dynamic soaring similarly as shear layers in the atmospheric boundary layer over plains, where vertical gradients in horizontal winds lead to energy gain as the sailplane climbs upwind and dives downwind. Other flight paths such as area-scanning and loitering can exploit dynamic soaring techniques as well.

The results obtained in the present study demonstrate the feasibility of aerial reconnaissance of canyons and craters on Mars using small sailplanes. The average flight altitude of the sailplane can be maintained or gained providing hours and days of flight by harvesting the energy from the atmosphere combined with auxiliary propulsion unit.

D.5 Athena: The First-Ever Encounter of a Main Belt Asteroid with a SmallSat

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The Athena Science Team

Athena is a mission concept to explore one of the largest main belt asteroids to reveal the role of water in the formation and evolution of protoplanets. Our proposal to the 2018 Small Innovative Missions for Planetary Exploration (SIMPLEx) opportunity was rated Category 1 but not selected. Here we will discuss how the Athena concept has evolved in preparation for future flight opportunities.

D.6 Lunar Mining Base Construction and Operation Using Teams of Small Robots

Jekan Thangavelautham
(*University of Arizona - SpaceTREx*)

Development of a space economy will require identifying and mining critical resources that will minimize cost and energy usage. The Moon is one potential candidate. It is rich in iron, titanium and silicon. Water is thought to exist in plentiful supplies in the Permanently Shadowed Regions (PSRs) of the North and South Pole of the Moon. Based upon these important findings, we plan on developing an energy model to determine the feasibility of developing a mining base on the Moon. This mining base mines and principally exports water, titanium and steel. The moon has been selected, as there are significant reserves of water known to exists at the permanently shadowed crater regions and there are significant sources of titanium and iron throughout the Moon's surface.

Our designs for a mining base utilize renewable energy sources namely photovoltaics and solar-thermal concentrators to provide power to construct the base, keep it operational and export water and other resources using a Mass Driver. However, the site where large quantities of water are present lack sunlight and hence the water needs to be transported using rail from the southern region to base located at mid latitude. Using the energy model developed, we will determine the energy per Earth-day to export 100 tons each of water, titanium and low-grade steel into Lunar escape velocity and to the Earth-Moon Lagrange points. Our study of water and metal mining on the Moon found the key to keeping the mining base efficient is to make it robotic. Teams of robots (consisting of 300 infrastructure robots) would be used to construct the entire base using locally available resources and fully operate the base. This would decrease energy needs by 15-folds. Furthermore, the base can be built 15-times faster using robotics and 3D printing. Furthermore, if we were to scale-up the resource output linearly, the base design and construction increases by the power law.

This shows that automation and robotics is the key to making such a base technologically feasible. The Moon is a lot closer to Earth than Mars and the prospect of having a greater impact on the space economy cannot be stressed. Our study intends to determine the cost-benefit analysis of lunar resource mining.

D.7 CubeSat-Sized Mars Solar Balloons for Aerial Exploration

Tristan Schuler and Jekan Thangavelautham
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Sergey Shkarayev
(*University of Arizona - Micro Air Vehicle Laboratory*)

Current methods of Mars exploration have relied upon flyby spacecraft, orbiters, landers and rovers. Orbiters such as the MRO with high-resolution camera such as HiRISE can provide unprecedented, high-resolution surface images from orbit, while rovers can carry state-of-the-art laboratories and obtained detailed images of local regions of Mars. There is an important need for next-generation robotic vehicles to obtain oblique views of large swathes of the surface and perform sample return. Autonomous aerial vehicles open up the opportunity to explore extreme terrains on Mars that previous robotic landers and rovers have been unable to reach. These aerial vehicles could help to solve some of unsolved mysteries on Mars. One of these mysteries is the observation of Recurring Slope Lineae (RSL) that have formed at the edge of crater walls, canyons, cliffs, slopes. Another is the seasonal observation of methane near the bottom of canyons and cliff walls.

From previous research, solar balloons have been found to be a feasible method of aerial exploration. Solar balloons using a lightweight envelope material with a high absorptivity and low emissivity to capture radiation from the sun. By including a vent, the balloon is also able to control altitude. For longitudinal control, the balloon can change altitude to ride the wind, which is predicted to flow in different directions at different altitudes similar to Earth. We explore different vent designs as well as types of attitude control that could be achieved with side vents.

If the solar balloon is deployed in the north pole during the summer, the balloon will maintain buoyancy for weeks at a time due to extended sunlight, however exploration on other parts of the planet introduces a major challenge due to the balloon cooling down and deflating at night. We will plan to run some laboratory experiments to test different methods to achieve buoyancy again after a night, including rigidizing the envelope and various internal lightweight structure designs.

E.1 Dynamic Power, SWaP reduction and Transceiver Sensitivity Enhancement in Interplanetary Small Satellites

Michael Hopkins
(*CurrentRF*)

Operating Power Conservation, long range signal transmit and receive fidelity, and overall signal cleanliness is everything in Interplanetary and Deep Space CubeSat systems. The power capability of these small systems limit the sensors, the transmitting capability, and the amount of onboard data processing that can be accomplished before transmission to a ground station. In 1U units the dimensions are roughly 100mm × 100mm, leaving very little space for solar panels, RTGs, and batteries. In 6U units the dimensions are larger (100mm × 226mm × 388mm), but the usable space is dedicated to larger instruments, processing electronics, and transceivers, again leaving little space for solar cells, RTGs and batteries, which have also grown in size to meet the power demands of the payload.

What is needed are methodologies, technologies, and devices that can reduce needed solar panel space, RTG size, and batteries. This can be done by re-cycling some of the dynamic current that is generally "thrown away" in dynamic digital processing and transmit/receive circuits, this re-cycling decreasing overall system power consumption and transmit/receive signal distortion. What is needed is a Power Saving and Sensitivity Enhancement System, embodied as the CC_100 PO/SSC IC and reference design, and it's various packaging configurations.

This TRL6 level, CC_100 PO/SSC IC (Power Optimizer/Silicon Super Capacitor) reduces dynamic power, as much as 36% of the total dynamic power usage, in digital circuits embedded in Interplanetary and Deep Space CubeSat payloads. The technology also reduces classical noise and residual, digitally coupled noise in Analog and RF systems, increasing RF and analog signal path system sensitivity and cleanliness. The CC_100 PO/SSC devices have proven to increase minimum receive signal sensitivity from -143dBm to -146dbm in practical receiver systems. This technology and methodology reduces SWaP of solar panels, RTGs, and batteries by 36% in Interplanetary and Deep Space CubeSat systems, or conversely, allows the sensor and processing systems to grow by 36%, given the same size Solar Panel, RTG, and Battery collection and storage systems.

E.2 LUNARAD – A Study of Radiation Shielding Technologies in Cis-lunar Space

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LunaRad is a collaborative project between the California Polytechnic State University's CubeSat Laboratory (CPCL), Kyushu Institute of Technology in Japan, and Nanyang Technological University in Singapore. The concept was proposed to the NASA CubeSat Launch Initiative for a launch onboard Artemis 2. The LunaRad project's primary mission targets the study of four types of radiation shielding technologies in cis-lunar space. The first shielding is aluminum, the most common material used for spacecraft structures. The other three shielding materials considered are used in astronaut suits and include ortho fabric (polybenzimidazole-based material), urethane coated nylon, and neoprene coated nylon. The shielding capabilities will be evaluated based on total ionization dose (TID) measurements using MOSFET sensors. To complement TID measurements, the analysis of linear energy transfer of protons and heavy ions will be carried out.

In addition to its primary mission, LunaRad will carry three secondary payloads: a chip scale atomic clock (CSAC), a camera, and an in-house developed radio for deep space communication. The CSAC payload is included to partially demonstrate navigation capabilities in cis-lunar space, the camera payload is included as a critical part of the outreach efforts undertaken by CPCL, and the in-house developed radio for deep space communication is included as part of CPCL efforts to develop a low cost radio with minimal mass, volume, and power requirements as a complement to the IRIS radio developed by NASA's Jet Propulsion Laboratory. In addition, the LunaRad project aims at creating hands-on, project-based learning opportunities and STEM awareness for more than fifty undergraduate and graduate students, who will be involved in the full LunaRad project life cycle. In particular, CPCL will engage the students in the design, manufacturing, test, integration, and operations of the CubeSat bus and payloads. The CPCL students have rich expertise across industrial manufacturing, mechanical, computer science, electrical, and aerospace engineering disciplines. In the presentation, the mission and CubeSat overall architecture will be discussed along with the mission risk analysis as well as the schedule and budget estimates.

E.3 Star Tracking for Small Satellites: Efficient Star Identification Using a Neural Network

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(*European Space Agency*)

The required precision for attitude determination in spacecraft is increasing, providing a need for more accurate attitude determination sensors. The star sensor or star tracker provides unmatched arc-second precision and with the rise of micro satellites these sensors are becoming smaller, faster and more efficient. The most critical component in the star sensor system is the lost-in-space star identification algorithm which identifies stars in a scene without a priori attitude information. We present an efficient lost-in-space star identification algorithm using a neural network and a robust and novel feature extraction method. Since a neural network implicitly stores the patterns associated with a guide star, a database lookup is eliminated from the matching process. This makes the search time O(1). This algorithm provides state-of-the-art performance in a simple and lightweight design, outperforming classical approaches. The efficiency of the algorithm enables small satellites to use high performance attitude determination sensors.

E.4 RADIATION HARDNESS IN MAGNETORESISTIVE RANDOM ACCESS MEMORIES

Romney R. Katti
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Magneto-resistive Random Access Memories (MRAMs) have been developed, qualified, and made available as standard products for radiation-hardened, space, and aerospace applications. These MRAMs are also non-volatile, indicating they retain data even when unpowered. These MRAMs include single-die MRAMs in single-chip packages (SCPs) with capacities of 16 Megabits (16Mb), and four-die MRAMs in multi-chip modules (MCMs) that have capacities of 64 Mb. These 16Mb and 64Mb MRAMs are specified to operate across a temperature range of -40 °C to +125 °C; are QML-qualified for classes V and Q; and use Magnetic Tunnel Junctions (MTJs) fabricated on radiation-hardened 150nm silicon-on-insulator (SOI) CMOS to achieve desired functionality in radiation, space, and aerospace environments. The MTJs in these MRAMs use inductive Savtchenko toggle-bit writing and tunneling magneto-resistance (TMR) readback. MRAMs were subjected to heavy ion irradiation, and to total ionizing dose (TID), dose rate upset (DR-U), dose rate survivability (DR-S), and neutron exposure testing, to determine and to confirm radiation hardness and to identify failure mechanisms and the physics of failure. MRAMs were demonstrated, for example, to be robust to irradiation and radiation effects, meeting 1Mrad(Si) TID levels, DR-U thresholds of 1E10 rad(Si)/s, DR-S levels of 1E12 rad(Si)/s, and neutron (N) levels of 1E14 N/cm^2 (1 MeV equivalent).

No latch-up was observed in DR-U or heavy-ion testing. Heavy ion irradiation testing was also performed. For the heavy-ion species and cumulative fluence and LET conditions that were tested, the MTJs exhibited no hard errors for cumulative fluences exceeding 1E9 ions/cm^2 and approaching 1E10 ions/cm^2 for heavy-ion species with Linear Energy Transfer (LET) values up to approximately 55 MeV-cm^2/mg. Such performance supports use in radiation-hardened, space, and aerospace applications. When Ta is used as a heavy ion at an LET of 81.1 MeV-cm^2/mg, hard errors were induced in MTJs at a cumulative fluence level of approximately 1E7 ions/cm^2. As the cumulative fluence is increased to approximately 1E8 ions/cm^2 and then to levels approaching 1E9 ions/cm^2, and as the irradiation angle becomes more oblique, and away from normal incidence to increase the effective LET value to approximately 150 MeV-cm^2/mg, additional hard errors in MTJs were induced. While hard errors were induced in MTJs at what in practice are extreme conditions, the use of error correction with MTJs that exhibit sufficiently low magnetic bit-error rates supports operation with quantifiably low overall error rates.

E.5 End to End Strategies for Exploring Lunar/Martian Caves

Himangshu Kalita and Jekan Thangavelautham
(*University of Arizona - LPL and SpaceTREx*)

Some of the high priority targets outlined in the Planetary Science Decadal survey includes extreme environments of the Moon, Mars and icy moons that includes caves, canyons, pits, cliffs, skylights and craters. Exploration of these extreme and rugged environments remains out of reach from current planetary rovers and landers; however, the 2015 NASA Technology Roadmaps prioritizes the need for next-generation robotic and autonomous systems that can explore these extreme and rugged environments. We had presented an architecture of small, low-cost, modular spherical robot called SphereX that is designed to hop and roll short distances for exploring these extreme environments. The robot uses commercially off-the-shelf components for its electronics and communication. For mobility, the robot uses a miniaturized propulsion system consisting of one thruster along with a 3-axis reaction wheel system to perform controlled hopping and rolling. For power, the robot uses either lithium ion batteries or PEM fuel cells. For the robot to survive extreme temperature ranges on the target environment, it consists of a thermal control system that relies on both active and passive thermal control elements. Moreover, the robot has a payload in the form of a pair of stereo cameras for imaging and a LiDAR system for mapping and navigation.

In this presentation, we will present end-to-end strategies for exploring Lunar/Martian caves. A lander carrying multiple SphereX robots would descent nearby a cave and deploy the robots one by one using a spring-based mechanism similar to CubeSat PPOD. Each robot will then have three phases 1. Surface operation to approach the cave entrance, 2. Cave entrance maneuver where the robot has to perform soft-landing depending on the depth of the entrance, and 3. Sub-surface operation to explore the cave. To do this we developed an Automated Multidisciplinary Design and Control Optimization (AMDCO) software framework that can design the SphereX robot based on mission requirements like target body, exploration distance, and exploration time. The software provides a set of near-optimal solutions in terms of mass, volume, power and control that are tested on a virtual Lunar/Martian cave environment for planning and navigation. The LiDAR onboard collects 3D point cloud of the environment which are then registered to a global frame to create a global map of the entire environment and also to localize the robot in the absence of GPS or. Moreover, the maps generated are used for trajectory planning. Using this methodology, it is now possible to develop and test strategies for exploring Lunar/Martian caves.

E.6 Solar 3D Printing of Structures for Off-World Bases

Steven Anderson, Abraham Marquez, and Jekan Thangavelautham
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Kickstarting a space economy will require building communication relays, refueling depots, repair depots, hotels and mining bases from in-situ resources in strategic locations between Earth, Moon and Mars. It would be too expensive to transport all the raw material from the Earth's surface and hence new methods of material extraction and construction needs to be found.

Critical to these steps is the need for a low-cost and efficient means for construction of habitats and physical structures. Utilizing networks of small spacecraft and robots to perform the task will reduce cost, enable scalability and robustness. The idea of 3D printing structures has risen to the forefront of construction methods for its ability to be sent in advance of the primary mission and build structures autonomously. Two distinct challenges are inherent in this concept: the 3D printer needs to be supplied material and it must have the ability to generate a significant amount of heat to melt the material.

Refining this printing technology to be as energy and resource efficient as possible is of the utmost importance to future space missions. Once this is achieved it will be economical to build lunar and planetary bases in-situ. Reducing the necessary supply of material to the additive manufacturing process and the power consumption leads to a reduction in the size of these early missions.

In an effort to confront these challenges, we are working to develop an additive manufacturing process based on the principles of the Selective Laser Sintering (SLS) technique whereby a heat source (a laser in the case of SLS) heats the material its liquefaction point before returning to a solid form. By replacing the laser in the SLS process with a large Fresnel lens, we aim to focus enough sunlight to be able to liquefy the material and create solid shapes. In this way, the system fully relies on renewable solar energy for its operation.

E.7 Use of Lasers and FemtoSats to Explore the Lunar Permanently Shadowed Regions

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The Permanently Shadowed Regions (PSR) on the Moon are thought to hold vast reserves of water-ice that would be critical for future propellant production and sustaining a future human base. The previous LCROSS mission impacted into a PSR region, providing data to further strengthen this water-ice hypothesis. Future surface missions are needed to provide in-situ measurements of PSRs. However, the PSRs pose unique challenges because they are some of the coldest environments in the solar system, while being in perpetual darkness. As part of the NASA BIG Challenge, a team led by Colorado School Mines, in partnership with University of Arizona's SpaceTREx Laboratory and University of Colorado, Colorado Springs, propose to develop a laser emitter-receiver system to pave the way for lunar PSR exploration.

The system consists of a turret mounted on a CLPS lunar lander that will emit a laser beam onto a receiver deployed from the lander. The receivers will be ballistically launched using a spring deployment system. The laser beam will be used to power and communicate with the receivers. It is envisioned that these receivers are SunCube FemtoSats. The SunCube FemtoSats are miniature spacecraft that are low-cost, in the order of few hundred dollars each, have a mass of 35, 70 or 100 grams, disposable and can be sent in groups to perform exploration and networking studies. The FemtoSats could potentially light-up the PSR surface using LEDs of different wavelength for spectroscopic studies, obtain close-up picture of the regolith surface and characterize the surface topology and material from their impact. Considering the lunar PSRs are an unknown environment, it is logical to deploy low-cost disposable devices to get a closer look at it first. This technology demonstration will pave the way for powering and communicating with more sophisticated instruments and vehicles inside the PSRs using lasers deployed on areas of high illumination. The proposed mission is expected to last one lunar day (12 earth days).

F.1 Small Payloads for Lunar Exploration: Requirements and Challenges

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Increased opportunities to fly small orbital, lander, and/or rover platforms as part of one lunar mission/mission suite will greatly facilitate the meeting of high priority lunar science objectives that require distributed measurements to be fully realized.

For the Moon, these objectives include determining the global distribution and origin as well as resource inventory for water and other volatiles at local-scale resolution; monitoring and modeling the nature of the radiation/charged particle/exosphere/micrometeorite/surface/ subsurface interactions constituting the lunar environment; monitoring and modeling the lunar interior and constraining the Moon's history and origin; and developing potential ISRU resource, including water, inventories.

Compact and robust versions of instruments ranging from kilograms to ten kilograms integrated with small orbiter, rover or lander platforms of particular interest are already under development via NASA DALI, CLPS/NPLP, and SIMPLEX programs. These include compact and robust near to IR cameras and imaging spectrometers (e.g., EECam, mini-TES) to characterize surface composition and properties; neutron spectrometers, magnetometers, sub millimeter sounders, and seismometers (e.g., mini-NS, SEIS) to characterize the subsurface, energetic particle analyzers (mini-ESA, mini-ENA) along with mini tunable laser (mini-TLS) or mass spectrometers (mini-QITMS) to measure in situ gaseous species. Some distributed networks that could be envisioned include: 1) tens of mini-rovers to characterize subsurface water (with IR imagers, mini-neutron spectrometers, and mini-GPRs) to a depth of 1 to 2 meters traveling along traverses at several likely candidates for hundreds of ppm near surface water; 2) 5 to 10 low-altitude orbiters or mini-landers spaced over hundreds of kilometers that characterize the lunar water cycle (with solar wind analyzer, energetic neutral analyzer or mini-QITMS, and IR imager), and 3) several landers spaced over hundreds of kilometers that characterize the lunar interior (with seismometers, heat flow experiments requiring a small drill for deployment, and magnetometers.

A major challenge for small packages, particularly on the lunar surface, is thermal packaging to protect the payload from the lengthy temperature extremes without the need for active control systems requiring power and thus significantly increasing mass and volume needed for batteries during lunar night. High performance thermal component based packaging based on passive thermal design that will allow operation on at least limited duty cycle during lunar night is now being developed and tested through the STMD funded PALETTE project.

This work, pre-decisional information for planning and discussion purposes only, was performed in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

F.2 100-grams high spectral resolution spectrometer for SmallSat Planetary Missions

Sona Hosseini
(*Jet Propulsion Laboratory, California Institute of Technology*)

Mapping the distribution and composition of the species responsible for the UV emissions (e.g., atoms, molecules, ionic, and neutral) is critical to understanding the structure and evolution of Solar System and planets, including our own Earth-Moon system. Many planetary objects that produce UV emissions are angularly extended low brightness targets, i.e., solar wind charge exchange emission, solar system planetary atmospheres and exospheres, mapping atomic emission, comets, and the interplanetary medium. This presents a challenge to the observer as traditional slit-spectrographs lack the sensitivity to disperse the low photon flux into a large number of spectral resolution elements (R 100,000) and cannot detect the faint UV emission spectra from these important astronomical targets.

We will present the results of developing a 100-gram Spatial Heterodyne Spectrometer (SHS) for planetary CubeSats and robotic platforms. SHS is a relatively novel approach for high étendue, high R spectroscopy in a compact low-cost, low-mass, low-power architecture. It uses a small aperture telescope (or none) for UV to IR wavelengths. SHS based techniques have been making headway as an alternative to both Fabry-Perot interferometers (FPI) and Fourier-transform Spectrometers (FTS) and can be made extremely compact in a reflective design with no moving parts for narrow bandpasses. Our 100-grams HOLMS (Heterodyne OH Lunar Miniature Spectrometer) has an ultra-high spectral resolving power R=33000 and a wide angular FOV=6 degree over a short bandpass (306-3010 nm). HOLMS has low power (6 W), low data rate and can detect the hydroxyl ODOH isotope ratio remotely in diffused and faint targets such as cometary tails, comae, and planetary exospheres.

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

F.3 Compact QIT-Mass Spectrometers for Space Applications

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The JPL Mass Spectrometer Team develops spaceflight components and instruments based on the architecture of a Paul quadrupole ion trap mass spectrometer (QIT-MS). Over the past 20 years, the team has miniaturized the QIT-MS format significantly and verified its performance successfully aboard the International Space Station.

We validated the requirements for a lunar application in the laboratory and are in the process of preparing the QIT-MS for TRL 6 readiness. The performance includes identifying and quantifying exosphere species (ex. H, H2, 3He, 4He, Ne, N2, O2, Ar, CH4, CO, CO2, Kr, Xe, OH, H2O) with abundance greater than 10 moleculescm^3. Miniaturization results in the combination of low mass (7.5 kg), low power (30W with the heater on). The compact QIT-MS has high sensitivity (0.003 counts/cm^3sec) and ultrahigh precision validated in the laboratory, ex. 1.7 $\times$ 10-10 Torr, terrestrial Kr measured continuously for 7 hours, yielded a 0.6 precision on the 86Kr84Kr ratio [1]. These measurements will provide unprecedented insight into the physical processes taking place in the lunar exosphere, including those thought to contribute to the ions that make up the thin lunar exosphere. These processes could include interactions of the moon's surface with sunlight, the Earth's magnetosphere, micrometeorites, or other phenomena.

The QIT-MS applications are not only limited to the lunar exosphere because technology developments are underway to incorporate inlet systems for liquids and dust particles, which allow exploring ocean worlds and high-density atmospheres with similar sensitivities and precision in the future.

F.4 Thermal Toolbox Elements for Lunar/Planetary Extreme Environments

David C. Bugby and Jose G. Rivera
(*Jet Propulsion Laboratory, California Institute of Technology*)

Exploration systems/devices that can operate/survive in lunar/planetary extreme environments without radioisotopes will likely be highly sought after by NASA in future missions. To aid system developers, JPL is expanding its "thermal toolbox". Four thermal toolbox technologies are under development: (1) passive dual thermally-switched (low heat loss) enclosures; (2) affordable, low sink temperature parabolic reflector radiators (PRRs); (3) high-performance (ultra-low effective emissivity) multilayer insulation (MLI); and (4) high-performance (ultra-low conductance) thermal isolators. Technology development in these four areas is proceeding with JPL internal funding that will soon transition to NASA Game Changing Development (GCD) funding through a program called Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE). This paper will focus on the PALETTE program, which should start in April 2020, and only outline the JPL program (known internally as ARTEMIS-T). A companion paper will describe the JPL program in detail. Once PALETTE ensues, four additional thermal areas will be studied including bulk metallic glass (BMG) actuated gimbals, low heat loss feedthroughs/apertures, combined thermal switching/transport/storage devices, and system scaling/extensibility/planetary use.

The paper will also briefly describe other related thermal work at JPL, including a new thermal switch for non-vacuum environments and a thermal switching system that will fly on an upcoming lunar lander.

F.5 Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)

Bradley Cheetham
(*Advanced Space*)

Advanced Space has partnered with NASA to develop and build the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission which will serve as a pathfinder for Near Rectilinear Halo Orbit (NHRO) operations around the Moon. The NHRO, (Perilune = 3,200 km; Apolune = 70,000 km) will be the intended orbit for the NASA's Gateway lunar orbital platform, as such the CAPSTONE mission will validate simulations and confirm operational planning for Gateway while also validating performance of navigation and station-keeping for future operations. Thus, this mission will provide operational experience to NASA, commercial, and international missions for operations in a demanding orbital regime.

CAPSTONE will fly a 12U cubesat developed, integrated, and tested by Tyvak Nanosatellite Systems carrying a payload communications system capable of cross-link ranging with the Lunar Reconnaissance Orbiter (LRO), a dedicated payload flight computer for software demonstration, and a camera. The cross-link ranging and software demonstration will provide critical demonstration of the Cislunar Autonomous Positioning System (CAPS) to enable peer-to-peer navigation for future lunar missions. CAPSTONE is contracted to launch with Rocket Lab and will be delivered late 2020 for a launch in late 2020 or early 2021. Upon launch, the spacecraft will traverse a highly efficient transfer taking approximately three months to enter a primary demonstration phase in an NRHO for six months followed by a twelve month technology enhancement operations phase.

The CAPSTONE Project is led by Advanced Space, LLC of Boulder Colorado. Spacecraft development and mission operations will be conducted by Tyvak Nanosatellite Systems of Irvine, California. Noted objectives for the CAPSTONE mission will be to demonstrate the accessibility of NHROs, validate key operational concepts in the NHRO environment, lay a foundation for commercial support of future lunar operations and accelerate the availability of peer-to-peer navigation capabilities provided by the Cislunar Autonomous Positioning System (CAPS).

The CAPSTONE mission is funded through NASA's Small Spacecraft Technology Program (SSTP), which is one of several programs in NASA's Space Technology Mission Directorate. SSTP is chartered to develop and demonstrate technologies to enhance and expand the capabilities of small spacecraft with a particular focus on enabling new mission architectures through the use of small spacecraft, expanding the reach of small spacecraft to new destinations, and augmenting future missions with supporting small spacecraft. The CAPSTONE Mission and project status will be presented.

F.6 Lunar Far Side Tracking and Communication Relay System

Rahul Ravikumar, Vishal Latha Balakumar, Sanjay Nekkanti, Abhay Egoor, and Krishna Teja Penamakuru
(*Dhruva Space Private Limited*),
Dhruv Jain (*Purdue University, West Lafayette, Indiana*)

Overview: The P30 platform is a 300 x 300 x 300 mm structure which has a modular internal configuration that was tested successfully and allows for between 9U and 12U volume within an optimized, modular structure. The proposed design will include the P30 external structure as the 'Parent' spacecraft placed at the Earth-Moon L2 point for imaging and tracking operations, and multiple 1U CubeSats or 'children' deployed from the P30 to act as a communication relay to enable data transmission from the system to the ground station.

Payload: The capability to provide a customizable internal configuration for the Payload and additional space than generally available on a similar CubeSat platform is unique to the P30 structure and can be utilized for a wide range of applications. The P30 platform can accommodate upto 4 CubeSats of the 1U form factor that can be deposited at multiple locations in the same orbital plane and will help increase the downlink time for communication between the 'parent' satellite and the ground station.

The P30 structure, placed in a halo orbit at the L2 point, will consist of multiple instruments, including a high resolution multispectral imager for accurate tracking of ground based systems on the far side of the moon. Additionally, the spacecraft will contain an infrared spectrometer to enable thermal profiling of the region and identify the surface composition. The P30 'parent' spacecraft will allow for distributed correlation of the data that is then transmitted from the 'children' satellites for downlinking using a Disruption Tolerant Network (DTN). This system of satellites can assist the guidance and navigation of future landers and rovers exploring the area.

Mission Design: The platform will be designed to have a nominal mission lifetime of 3 years. The structure will include 3-axis attitude stabilization using magnetorquer coils. The inter-satellite link using the DTN system will be developed to enable autonomous data transmission between the 'children' and 'parent' spacecraft, to be downlinked to the ground station with minimal latency.

Furthermore, the 1U CubeSats will be developed based on the necessary application and integrated within the P30 platform. The P30 structure will be updated to include a deployment system for orbit insertion of the 1U CubeSats. Further research will be conducted into control of the internal thermal environment and communication capabilities with respect to interplanetary missions.

F.7 Smallsats Beyond Saturn Without Radioisotopes: A Preliminary Assessment

Robert L. Staehle, Alessandra Babuscia, Nacer Chahat, Steve Chien, Corey Cochrane, Courtney Duncan, Henry Garrett, Damon Landau, Paulett Liewer, Pantazis Mouroulis, Neil Murphy, Adrian Tang
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(*California Polytechnic University*),
Kian Crowley (*Crowley Aerospace Consulting*), Jekan Thangavelautham
(*University of Arizona - SpaceTREx*)

Few spacecraft have explored the outer Solar System beyond Saturn's orbit. Thus, there remain many valuable scientific opportunities to explore. With the right application of emerging technologies, it appears that small spacecraft could provide a viable architecture for some such missions by ridesharing with larger spacecraft going to Jupiter or Saturn. So far, deep space interplanetary exploration has been unachievable by low-cost small satellites. The Outer Solar System SmallSat (OS4) architecture concept addresses how to overcome many present barriers, including the expense of carrying radioisotopes for heat or electric power. Our NASA Innovative Advanced Concepts (NIAC)-sponsored concept development suggests that a design could be effective out to Neptune's 30 AU orbital distance from the Sun. With more thermal insulation development or lower allowable flight temperatures, the maximum distance may be increased. All spacecraft venturing past Jupiter to date have carried radioisotope thermoelectric generators (RTGs) to provide power. In order to reduce overall mission cost and the complexity of securing launch approval, OS4 would use solar power concentrated by an inflatable solar concentrator large enough to generate needed power even at large solar distances. Concentrators up to 5 m in diameter appear viable for rideshare launch packaging. Taking into account the available energy density, OS4 would have to operate on very low power. However, enough electrical power must be provided to maintain electronics above minimum temperatures within a well-insulated enclosure to limit heat loss. In early stages of a mission, off-Sun pointing, radiators, and a reverse thermal switch could enable shedding the excess thermal energy that the solar concentrator focuses on the spacecraft. To retain thermal energy farther from the Sun, multi-layer insulation could be used in conjunction with duty cycling and phase-change material surrounding sensitive electronics to make use of waste heat from less frequent RF transmissions. Deep space communications appear viable using the inflatable solar collector as a communications dish. Because of their relatively low cost and small stowed configuration, spacecraft using the OS4 architecture would be able to rideshare on ESPA rings and be deployed to multiple destinations. By lowering the cost barrier for science in the outer Solar System, the OS4 architecture appears able to provide promising new opportunities.

6. Poster Session

P.1 Inflatable membrane reflectors for small satellite telescopes

Aman Chandra, Siddhartha Sirsi
(*Department of Astronomy and Steward Observatory, University of Arizona*),
James C Wyant
(*College of Optical Sciences, University of Arizona*)
Heejoo Choi, Christopher Walker, Dae Wook Kim, and Yuzuru Takashima

Imaging distant objects with increasing spatial resolution is required to further space exploration abilities. Telescopic imaging of exoplanets and other objects require increasingly large collection surfaces in the form of mirrors. Such mirrors when used at terahertz frequencies can further capture object chemistry, mass structure and dynamics. Membrane mirrors could lead to a dramatic scale up in size of deployed energy collection surfaces. Very low areal density and high packing efficiencies have led to inflatable membrane mirrors being considered as a key- enabling technology. Membrane reflectors built in the past have faced challenges of unreliable surface shape and uncontrolled dynamics. A major source of inaccuracies comes from manufacturing techniques employed. The final shape attained by inflated membrane reflectors can be modelled as oblate spheroids in between a perfect sphere and parabola. Conventionally, inflatable mirrors are built out of segmented gore units leading to faceted final shapes. They have also not been found to be repeatable, thus making it difficult to design corrective optics. The gore assembly process does not scale well with size due to additional complexities of precise assembly of these units together. Membrane reflectors can be deployed with corrective optics if their inflated shape is repeatable and reliable.

Continued

P.1 Inflatable membrane reflectors for small satellite telescopes

Aman Chandra, Siddhartha Sirsi
(*Department of Astronomy and Steward Observatory, University of Arizona*),
James C Wyant
(*College of Optical Sciences, University of Arizona*)
Heejoo Choi, Christopher Walker, Dae Wook Kim, and Yuzuru Takashima

Our present work focuses on thermal forming of thermo-plastic membranes to desired shapes. This method involves heating a 1-meter diameter circular membrane close to its glass-transition region with the heated membrane inflated and held at a constant temperature using a jig designed to control circumferential tension. This leads to a bi-axial stress state causing a retention of induced curvature when cooled down and leading to a controlled curvature when re-inflated. This method eliminates breaking down the membrane into gore units and can be scaled over to vast membrane sizes. A set-up has been designed and built to thermally form a 1-meter diameter Mylar membrane reflector and conduct shape measurement on its surface.

We present results of optical photogrammetry to characterize membrane surface figures upon repeated inflation cycles. The results are used to validate thermo-structural simulations conducted on the expected membrane surface behavior. A deployment system has been developed to package the membrane mirror and optics into a 3U form factor making it a suitable payload for CubeSats ranging in size from 6U and above. Our work contributes towards an understanding of key design variables in the development of tensioned thermally formed membrane reflectors for small satellite telescopic imaging systems.

P.3 NASA Cubesat and Microsat Cost Model Tool

Joseph Mrozinski, Michael Saing, Melissa Hooke, Alex Lumnah
(*Jet Propulsion Laboratory, California Institute of Technology*),
James K Johnson
(*NAS Headquarters*)

The "CubeSat Or Microsat Probabilistic and Analogies Cost Tool", or COMPACT, is a NASA Headquarters funded effort to fill the gap in cost estimating capabilities for CubeSats, as well as other Microsat spacecraft. The COMPACT team has been collecting mainly cubesat mission's technical, programmatic, and cost data to date from various NASA sponsored programs led by NASA, research laboratories, and/or universities. The COMPACT team has developed a prototype cost modeling approach using k-nearest neighbors (k-NN). This approach can be used in early concept maturity study phase to get a ballpark cost estimate grounded by historic actual costs and design. The presentation will demonstrate the use of k-NN with COMPACT data on its web base platform.

P.4 Small Satellites for Mars Exploration

Pamela Clark, Nathan Barba, Vlad Stamenkovic,
Tomas Komarek, Louis Giersch, Ryan Woolley
(*Jet Propulsion Laboratory, California Institute of Technology*)

Mars Smallsat Study The Mars Exploration Directorate at the Jet Propulsion Laboratory is sponsoring a study to examine technical feasibility of developing small spacecraft missions capable of compelling MEPAG science for low cost. Two examples, LOKI and SHIELD, are given below.

Instruments The study began by surveying science instruments for MEPAG high-priority investigations suited to mass, volume, power, and cost constraints of a small spacecraft. These instruments include compact versions of a camera (MSL EECam), Meteorology (MEDA-ATS or FMI wind, barometry, T, and P), Seismometer (INSIGHT SEIS), Atmosphere (MSL TLS), and Dust (ExoMars MicroMED) analyzers.

LOKI (LOcalizing Key Ingredients): This Areostationary SmallSat orbital constellation investigation would localize sinks and sources of trace gases to constrain the processes controlling methane and oxygen distribution on Mars. Areostationary orbits would allow the constant and large field of view lacking in previous trace gas monitoring.

SHIELD (Small High Impact Energy Landing Device): This new lander technology would reduce landing costs for small payloads (up to 6 kg). Landing decelerations are significantly higher than more conventional Mars EDL technologies, roughly 9,800 m/sec^2, or 1000 g, thus not all payloads will be compatible. (Product-level drop impact tests of cellular phones indicate that a cell phone dropped from 1 m can experience up to 1400 g [1]). SHIELD concepts include TH2OR, that would search for subsurface liquid water using a time-domain EM sounder to depths of many kilometers [1].

Continued

P.4 Small Satellites for Mars Exploration

Pamela Clark, Nathan Barba, Vlad Stamenkovic,
Tomas Komarek, Louis Giersch, Ryan Woolley
(*Jet Propulsion Laboratory, California Institute of Technology*)

Conclusions Small spacecraft missions can conduct traceable and compelling science, offering payload capability of <=20 kg for orbiters and of <=6 kg for landers. A first order analysis on cost indicated a single spacecraft in areostationary orbit would be under the $250 million cost target and a constellation of three small orbiters estimate cost could fit within the current $500 million Discovery class mission cost cap. The cost target for a SHIELD lander is estimated to be <$50M per lander or <$250 million for up to three SHIELDs, a transit stage, and launch.

References
[1] Ong (2003) IEEE Electronics Packaging Technology;
[2] Stamenković et al. (2019), Nature Astronomy 3, 116-120;
[3] Burgin et al., (2019), AGU Fall, P44B-02.

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P.5 Observation Geometry for SmallSats

Charles Acton
(*Jet Propulsion Laboratory, California Institute of Technology*)

NASA's SPICE system provides users a well-crafted means to compute a wide assortment of mission geometry parameters needed for planning science instrument observations to be taken from interplanetary spacecraft, and to subsequently help with analysis of the data returned from those observations. SPICE is similarly used by engineers involved in designing missions and conducting mission operations. Positions and velocities, latitudes and longitudes, lighting angles and instrument footprint projections are among the many kinds of calculations that can be made using SPICE.

The SPICE system is comprised of a large suite of APIs (subroutines) and an assortment of ancillary data files. Users integrate a few selected APIs into their own purpose-built application programs designed to plan science observations, conduct engineering tasks, or analyze science data. The software is offered in many popular languages and for most popular computing platforms. That software is highly documented and well tested, so it may be used with confidence. It is multi-mission by design, so can be used over-and-over. Even better, it is free to everyone and is not restricted under export or licensing rules.

Also part of the SPICE family are a 3D mission visualization tool (Cosmographia) and an on-line GUI-driven geometry engine (WebGeocalc). The SPICE system developers provide a set of tutorials and open-book programming lessons to help newcomers learn how to use SPICE. They also offer a free three-day training class about once every eighteen months (maybe more often in the future). SPICE was originally used on the Magellan mission to Venus, and has been used on almost all worldwide planetary missions since then. It is also used in support of a number of heliophysics and earth science missions.

During this conference the SPICE developers hope to acquaint the SmallSat community with the existence of this very useful, well-proven mission geometry system. A demo table should be available for those who wish to learn more.

For further information: naif.jpl.nasa.gov

P.6 Architecture Trades for Accessing Small Bodies with an Autonomous Small Spacecraft

Benjamin Hockman, Saptarshi Bandyopadhyay, Reza Karimi, Issa Nesnas, Shyam Bhaskaran (*Jet Propulsion Laboratory, California Institute of Technology*), Sandro Papais
(*McGill University*)

Characterizing the composition, properties, and environments of Small Bodies is key to understanding the origins and processes of the Solar System. Traditionally our knowledge has been limited to ground observation and select few missions which cannot fully characterize the diversity of Small Bodies. Advances in miniaturized spacecraft technologies have recently enabled small spacecraft to perform missions in deep space, as demonstrated by Mars Cube One in 2018. Additional missions are being developed to further mature these technologies and expand their capabilities. We investigate a new approach to exploring Small Bodies, where standalone small spacecrafts can be used as a more affordable approach to autonomously navigate, rendezvous, and characterize them. We review relevant mission concept studies, required technologies, available targets, architecture trade-offs, and baseline mission design options.

We show that using near-term technologies, available in less than 3 years, it is possible for a standalone small spacecraft to rendezvous with several Small Bodies. It was found that a 24 kg and 180 kg spacecraft would be capable of delivering payloads of 1.5 kg and 10 kg respectively to several interesting near-Earth asteroids candidates. Critical enabling technologies were identified as highly-capable (delta-V>3 kms) miniature electric propulsion system, high-efficiency (power density>100 Wkg) deployable solar arrays, and improved onboard autonomy algorithms. Advances in miniaturized instruments, high-performance radiation-tolerant avionics, and interplanetary communications systems can also be leveraged. In the long term, this architecture could enable a fleet of standardized autonomous small spacecraft to perform a cursory exploration of a representative sample of the Small Body population.

P.7 Test Capabilities Applied to Space Rate Sensors for Tactical and Space Inertial Reference Navigation and Small Satellite Applications

Romney R. Katti
(*Honeywell Aerospace*)

Inertial Reference Units (IRUs) are key components for angular rate sensing for guidance, navigation, and control in tactical, space, small satellite (small sat), and cube satellite (cube sat) applications. Test capabilities are described that were selected to demonstrate capability of a three-axis HG4934SRS Space Rate Sensor (SRS). As an example, the HG4934SRS uses tactical and space rated parts with performance that includes a dynamic range of 200 degreessecond, maximum 3gyro bias (including repeatability, where 3equals three standard deviations) of <225 degreeshour, in-run 3bias stability (over temperature at >0.75 °Cminute) <3 degreeshour, and 3 scale factor less than 3000 parts per million; with a mass <145 g, volume <82 cubic cm, <3 W nominal power consumption, <5.5 W peak power consumption, 5 V 10% power, mission life >6 years including for Low Earth Orbit (LEO) missions, storage life >10 years, and an operating temperature range spanning -41 °C to 71 °C.

To support expected life estimation, risk assessment, confidence analysis, mission class categorization, development, and qualification for component, module, and system applications, testing that such IRUs must pass are based on available test capabilities. Such test capabilities include environmental, electro-magnetic, and radiation environments testing. Environmental (ENV) testing and test capabilities performed at or by Honeywell in Minneapolis, MN, include vibration, shock, sine vibration, half-sine shock, acoustic, temperature, temperature shock, temperature/altitude, rapid decompression, and temperature/humidity testing, performed, e.g., per MIL-STD-810. Electro-magnetic interference (EMI) testing and test capabilities performed at or by Honeywell in Minneapolis, MN, include conducted susceptibility (CS), conducted emissions (CE), radiated susceptibility (RS), and radiated emissions (RE) testing performed, e.g., per MIL-STD-461. Radiation environments testing and test capabilities include total ionizing dose (TID) and single-event effects (SEE) performed, e.g., per MIL-STD-883, MIL-STD-750, MIL-HDBK-814, ESCC 22900, and ESCC 25100. Radiation test capabilities, such as for TID and SEE testing, were applied by Honeywell, Clearwater, FL, which features a full suite of in-house radiation test sources, analysis tools, and resources, in coordination with Honeywell, Minneapolis, MN, and other sites. Passing results were obtained for levels of interest, such as for natural radiation (e.g., LEO) with TID >18 krad(Si) and an SEE MTTF >2,000 years. Latch-up and functional interrupts are managed via fault detection and correction (FDC) and power management.

P.8 Atmospheric Flight Mechanics on Other Planets

Adrien Bouskela and Sergey Shkarayev
(*University of Arizona*)

The successful deployment of sailplanes on other planets of the solar system can provide a high volume of scientific data at a relatively low cost. Sailplanes can fly without power limitations by exploiting atmospheric wind gradients and shear layers for dynamic soaring, as well as slope and thermal updrafts for static soaring.

In the present work, aerodynamic studies have been conducted identifying general principles of sailplane design and flight maneuvers in different atmospheric conditions. The proposed sailplane concept features a blended-wing-body configuration with a sweptback flying wing. For times of unfavorable wind conditions, an auxiliary propulsion unit is added utilizing a small electric motor driving a retractable propeller. The propeller unfolds and motor turns on when additional thrust is needed. When wind conditions exceed the minimum requirements, the propulsion unit extracts the energy from soaring cycle recharging the batteries. The preliminary sizing of an aircraft was carried out taking into account mission requirements and atmospheric conditions. Specifications of sailplanes and main performance data were obtained for flights on Mars, Titan, and Venus.

Flight dynamics simulations of the sailplane on other planets have been conducted based on the three degrees of freedom model. The governing system of differential equations is written in terms of the state and control vectors. Planetary boundary layer models with linear wind profile are utilized in the analysis. In order to find a flight trajectory maximizing the sailplane energy, the constrained optimization problem is formulated. Its objective is to maximize the rate of change of the relative kinetic energy subject to the constraints on the airspeed.

The purpose of a series of numerical simulations was to characterize the energy efficiency of different segments of flights: climb, climbing turn, dive, and diving turn. They showed how the energy can be optimally extracted from the wind maximizing the travel distance or flight time. Sailplane performance characteristics for flights on Mars, Titan, and Venus are reviewed.

An experimental validation of energy gaining flights in environments with low atmospheric density has been conducted using test flights on the Earth. A sailplane was carried to a stratospheric wind shear region by a weather balloon, where the sailplane flew typical dynamic soaring trajectories. Obtained data were compared to results of numerical simulations.

P.10 Using Small Satellites as an Interplanetary Data Highway

Rahul Ravikumar, Vishal Latha Balakumar, Sanjay Nekkanti, Abhay Egoor, and Krishna Teja Penamakuru
(*Dhruva Space Private Limited*)

Overview The P30 platform is a 300 × 300 × 300 mm structure which has a modular internal configuration that was tested successfully and allows for between 9U and 12U volume within an optimized, reconfigurable structure. The proposed system will include the P30 external structure as the 'Parent' spacecraft and multiple 0.5U CubeSats or 'children' deployed from the P30 to act as an interplanetary communication relay or information highway, for efficient data transmission using small satellites.

Payload The capability to provide a customizable internal configuration for the Payload and additional space than generally available on a similar CubeSat platform is unique to the P30 structure and can be utilized for a wide range of applications. The P30 platform can accommodate up to 8 CubeSats of 0.5U form factor that can be deposited at various orbital planes with magnetometers, enabling high harmonics characterization. The network of small satellites will be placed in lunar orbit and will communicate with surface landers and rovers and relay data to the P30 'parent' satellite. The system will include an integrated communication system, based on a Disruption Tolerant Network (DTN), as well as an on-board propulsion system to enable orbit insertion. This design will greatly enhance data assimilation capabilities in interplanetary missions and reduce the latency time for downlinking of data.

Mission Design The platform will be designed to have a nominal mission lifetime of 3 years. The structure will include 3-axis attitude stabilization using magnetorquer coils. The inter-satellite link using the DTN system will be developed to enable autonomous data transmission between the 'children' and 'parent' spacecraft, to be downlinked to the ground station with minimal latency. The various subsystems such as the EPS (Electrical Power Supply) and the OBC (On-board Computing) will be designed in-house according to the requirements of the payloads.

Development Status The P30 structure has been already proven to be flight-capable and current development will be focused on minor updates of the design of the external structure and the necessary interface components to meet interplanetary flight requirements. Additionally, the 0.5U CubeSats will be developed based on the communication requirements and integrated within the P30 platform. The 'parent' structure will be updated to include a deployment system for orbit insertion of the 0.5U CubeSats. Further research will be conducted into control of the internal thermal environment and communication capabilities with respect to interplanetary missions.

P.11 Gravitational Perturbation Measurements in Martian Orbit

Rahul Ravikumar, Vishal Latha Balakumar, Sanjay Nekkanti, Abhay Egoor, and Krishna Teja Penamakuru
(*Dhruva Space Private Limited*)

Overview

The P30 platform is a 300 × 300 × 300 mm structure which has a modular internal configuration that was tested successfully and allows for between 9U and 12U volume within an optimized, modular structure. The proposed design will include multiple 2U CubeSats deployed from the P30 to conduct gravitational field measurements in Low Martian Orbit and perturbations due to Phobos and Deimos (Martian moons). The CubeSats shall be deployed in the same orbital planes at different true anomaly and obtain the change in distance and acceleration between CubeSats to calculate the higher order harmonics of the gravitational field.

Payload

The capability to provide a customizable internal configuration for the Payload and additional space than generally available on a similar CubeSat platform is unique to the P30 structure and can be utilized for a wide range of applications. The P30 platform can accommodate up to 3 CubeSats of the 2U form factor that can be deposited into circulars orbits around the Martian moons with 2 Cubesats in an orbital plane and third CubeSat with P30 in another plane. The spacecraft can perform a thorough differential modeling of the gravitational perturbation due to the moons.

The P30 'parent' spacecraft will allow for distributed correlation of the data that is then transmitted from the 'children' satellites for downlinking using a Disruption Tolerant Network (DTN). This system of satellites can assist the guidance and navigation of future orbiters and landers and provide a better profile of the gravitational environment.

Mission Design

The platform will be designed to have a nominal mission lifetime of 3 years. The structure will include 3-axis attitude stabilization using magnetorquer coils. The inter-satellite link using the DTN system will be developed to enable autonomous data transmission between the 'children' and 'parent' spacecraft, to be downlinked to the ground station with minimal latency.

Furthermore, the 2U CubeSats will be developed based on the necessary application and integrated within the P30 platform. The P30 structure will be updated to include a deployment system for orbit insertion of the 2U CubeSats. Further research will be conducted into control of the internal thermal environment and communication capabilities with respect to interplanetary missions.

P.12 Automated Swarm Architectures for Planetary Moon Impactor Missions

Ravi Teja Nallapu and Jekan Thangavelautham
(*University of Arizona - SpaceTREx*)

Impactor missions have provided a valuable platform to explore the interior of small bodies. In these missions, a carrier spacecraft releases a deadweight called the impactor, which ballistically, collides with the target small body exposing the interior in the vicinity of the impact site. Then, depending on the mission objective, either the impact site or the debris plume is studied by other participating spacecraft in the mission. Impactor missions have been successfully used to explore the interior of comets in the past and have also been proposed to explore several other small bodies in the near future. However, the design of impactor missions is a complex problem, as it involves the design of several key parameters. For instance, the instrument used for studying the impact site will influence the design of the swarm, by constraining the radius of approach to the target, and this, in turn, will influence the interplanetary trajectory of the swarm. In these cases, traditional mission design methods where each subsystem is separately designed can result in suboptimal performance.

For this reason, we have developed the Integrated Design Engineering and Automation of Swarms (IDEAS), which automates the design of spacecraft swam missions to small bodies. In this work, we present the application of the IDEAS architecture to design an impaction mission to explore planetary moons. Specifically, we design a swarm mission to explore the Martian moon Deimos, where the swarm has an impactor spacecraft that collides at a target location of interest. The remaining spacecraft in the swarm, consisting of Observer, and a Leader spacecraft, will enter resonant co-orbits around Mars, to for reconnaissance of the impact site on Deimos. The swarm will be optimized using the IDEAS architecture to meet a temporal coverage mission requirement using a minimum number of spacecraft. The results will demonstrate the capability of IDEAS to automate the design of a swarm mission with an impactor to explore the interior of planetary moons, thus enabling the design of better missions to explore the solar system.

P.13 Development of Small Body Gravitational Airbearing for Nano-spacecraft Testing

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Exploration of asteroids is high-priority science because it can provide insight into the origins of solar system, Earth and life on Earth. There are estimated to be more than 2,000,000 asteroids of which nearly 700,000 have been detected. Asteroids are often many billions of years old and have undergone steady activity that changes the surface properties of asteroids. This includes weathering phenomena that impacts the first few centimeters of an asteroid surface and leaves the internal material hidden from sight. The most effective way to understand the physical processes that created an asteroid and its contents would be through sample and return exploration. Sample and return missions for rubble pile asteroids such as Ryugu and Bennu have proven more difficult than expected for a number of reasons including the micro-gravitational environment as well as unexpected topographies. The recent discovery by OSIRIS-REx that Bennu is regularly ejecting particles into space presents an alternative path to collect samples without actually touching down on the surface.

In our concept, teams of deployed nano-spacecraft are tasked to intercept these particles in flight and return them to the parent spacecraft. Risk reduction for such a mission could be accomplished by testing prototype spacecraft on a classic planar airbearing, but with a curved surface to approximate the low gravitational environment of a rubble pile asteroid. This presentation explores the benefits of such testing, and derives requirements for such an airbearing table, including the size, cost, leveling and manufacturing tolerances. Finally a prototype section of the airbearing surface is built to characterize and demonstrate the basic testing concept.

P.14 Multipoint Observation of Europa Plumes Using FemtoSat Swarms

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The search for life beyond Earth remains a high-priority for the US Space Program. Since the start of the space program in 1957, we have learned events in outer space have been instrumental in seeding and evolving life on Earth. Meteorites which are the remains of asteroids have been shown to contain biochemicals including amino acids, the building blocks of life. Rare earth organisms are known to live in the upper atmosphere, and some are known to withstand the vacuum of space. The evidence suggest life is able to survive under very harsh conditions.

Jovian moon Europa is known to have more water that all the Earth's oceans combined. Europa is hypothesized to have a liquid-water ocean containing enough nutrients and warm temperatures to sustain life. Yet the surroundings of Europa are extreme, due to the high-radiation created from Jupiter's magnetic field and low-temperatures, being far from the Sun. Yet Europa's ocean is protected with a thick layer of ice thought to be several kilometers thick. There is currently no feasible technique to break through the Europa ice layer and get into the ocean. Instead we can rely on plumes which are hypothesized to be outbursts of water from cracks in the ice sheet. Sampling these plumes could give us insight into the composition of the water and further collect evidence for life to exist or not in the ocean underneath.

The main objective of this research is to develop new technologies and mission concepts to rapidly measure the plumes for evidence of life. The plumes of Europa are rare and thought to spread over a wide zone reaching altitudes of several hundred kilometers. There is a need for multipoint measurements of the plume to look for trace evidence of life. For this purpose, we propose the design and deployment of FemtoSat swarms that are equipped with spectroscopic LEDs to look for biological metabolism pathways.

The mission concept is divided into three parts: modeling Europa's plumes, study the different trajectories that the FemtoSats could follow to study the plume (basically orbit design) and finally advanced design of the FemtoSats to search for life.

For the plume modeling a statistical model for size, number and speed of particles is recreated. When designing the orbits of the FemtoSat it has to be accounted for the instability of high inclination orbits and fuel limitations. Finally, the main instrument of the FemtoSats would be a LED-based spectrometer that can detect life.

P.15 Beyond Touch and Go: Evolving Bipedal Walking Maneuvers for a Spacecraft on Stilts to Explore Asteroid Surfaces

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Exploration of asteroids and comets will help to answer fundamental questions about the origins of the solar system. There are estimated to be nearly 2 million asteroid and comets in the solar system, and they are strategic locations for planetary science, planetary defense/security and for resource mining. Landing on these small bodies and manipulating their surface remains a major technical challenge fraught with high risk. The low gravity and low cohesive forces holding dust, gravel, and boulders together could result in surface ranging from ‘quick sand’ to a hard gravel surface. The latest asteroid missions such as Hayabusa II and OSIRIS-REx will perform touch and go operations to mitigate the risks of ‘landing’ on an asteroid.

Beyond these missions, there is an important need to perform surface and subsurface sampling from multiple points on an asteroid. The SPIKE (Spacecraft Penetrator for Increasing Knowledge of NEOs) spacecraft architecture is unique in that it is a hybrid combination of an orbiter and lander. The orbit extends out a low-mass, high-strength boom that has a series of in-situ instruments at the tip to sample the surface and subsurface of the asteroid from a distance. In this work, we generalize the SPIKE spacecraft concept by utilizing the latest advances in automated computer design of the spacecraft to optimize the size, shape and number of booms mounted with instrumentation to perform multiple hops and walks on an asteroid surface. In our approach, we evolve a spacecraft to walk-bipedal on a low-gravity asteroid surface environment. We further analyze the implications for low-gravity on walking, namely keeping balance and maintaining traction. Our studies are used to determine how innovation occurs and when an efficient walking maneuver is discovered through an evolutionary approach.

Utilizing a pair of slender legs to walk, the spacecraft may resemble a flamingo walking gracefully in muddy ponds. There however remain uncertainties with the asteroid surface material, hardness and overall risk posture on the mission. Using this proposed design, we refinery our preliminary landing system and analyze the implications of GNC on science operations. Furthermore, we analyze a range of asteroid targets and potential variations in design to address the centi and milli-gravity surface environment. The proposed spacecraft design and controls approach is a major departure from conventional spacecraft with amphibious capabilities of a lander and orbiter vehicle packaged in one.

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