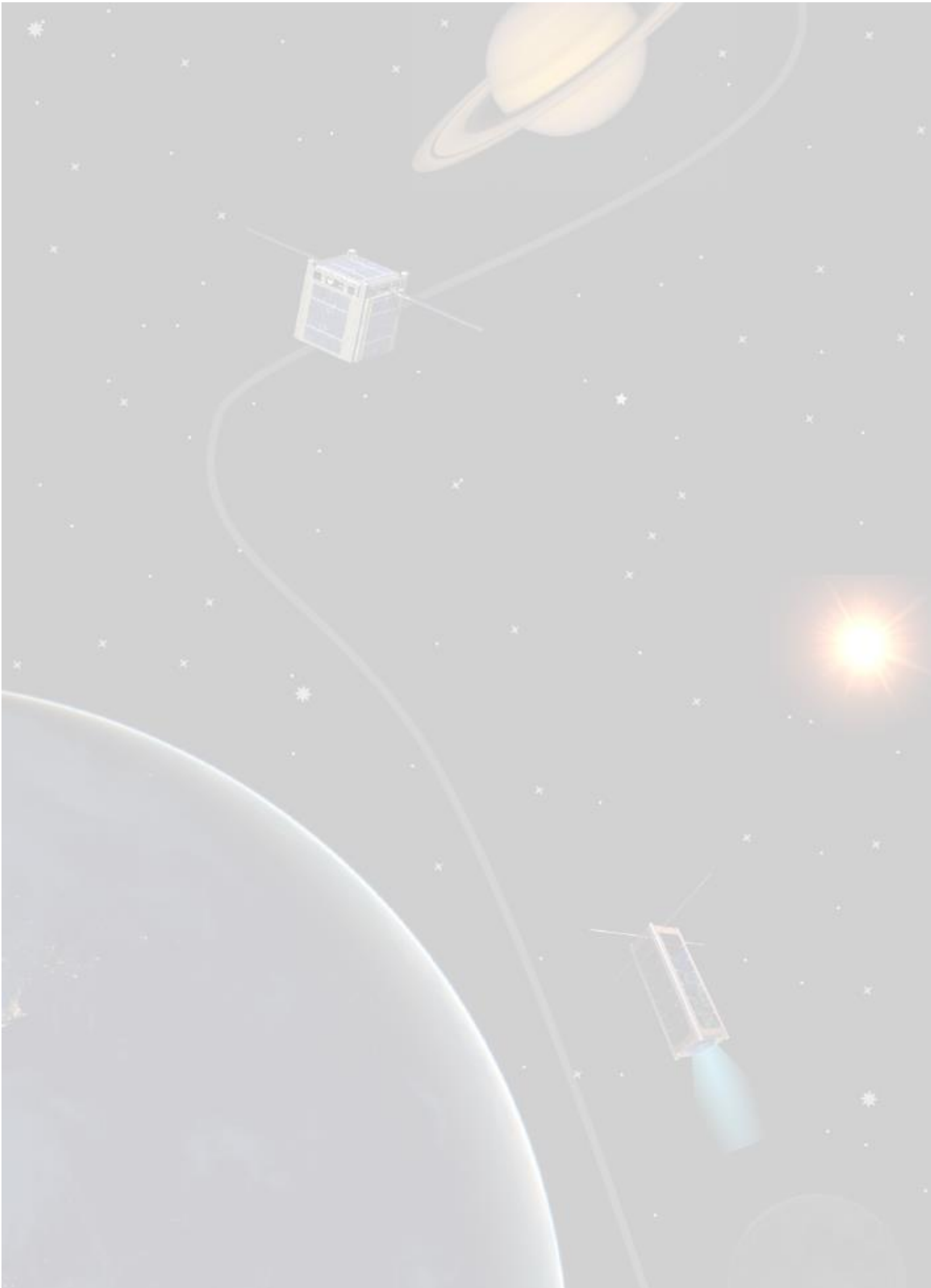
April 29th -May 1st 2025

California Institute of Technology



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Conference Agenda

Tuesday, 29th April, 2025

Time (PDT)	Event
7:30-8:45	Registration and Breakfast
8:45-9:00	**Opening Remarks (A. Babuscia)**
9:00-10:00	**Keynote Speaker: Dr Leon Alkalai (Mandala Space Ventures)** **Navigating the Emerging Commercial Space Ecosystem** *Moderator: A. Babuscia*
10:00-10:20	Coffee break
10:20-11:50	**Session A: Lessons learned from interplanetary small satellite missions recently launched or ready to launch** *Session Chairs: A. Babuscia and J. Thangavelautham*
	A.1 ESA Interplanetary Small Spacecraft Missions: Pushing the Boundaries of Miniaturized Systems & Technologies *(S. Simonetti)* A.2 CAPSTONE's Mission Extension: Navigating the Future of Cislunar Technology *(T. Gardner)* A.3 Designing and Producing interplanetary spacecraft resilient to requirements evolution *(C. Mandy)* A.4 Chimera-1: Accelerated Custom Platforms for Space *(A. Zhang)* A.5 The role of Small Satellites in Asteroid studies and Planetary Defense missions: the Hera Milani and Ramses CubeSat 1 *(M. Cardi)* A.6 BioSentinel Mission Update: Two Years and Counting in Deep Space *(J. Fusco)*
11:50-12:20	**Session A Q&A Panel: A. Babuscia and J. Thangavelautham**
12:20-13:15	Lunch
13:15-14:45	**Session B: Telecommunications, C&DH, and radar technologies for interplanetary missions** *Session Chairs: C. Lau and C. Lee*
	B.1 CubeSat enabled Differential Absorption Radar for Lunar water mapping *(A. Chandra)* B.2 The UST-Lite Radio: A multi-channel software-defined transponder for spacecraft and surface assets at the Moon, Mars, and beyond *(D. Ogbe)* B.3 The Arke Low SWaP Transponder for Mars and Lunar Missions *(Z. Towfic)* B.4 Edge AI/ML Model Processing for Near-Earth and Deep Space Missions Using Qualcomm Snapdragon *(S. Doran)* B.5 C-DST: a CubeSat platform for Deep-Space communication link *(R. Di Zitti)* B.6 Preventing Mission-Ending Failure: Lessons from and Changes to the Iris Radio *(T. Russell)*
14:45-15:15	**Session B Q&A Panel: C. Lau and C. Lee**
15:15-15:45	Coffee Break
15:45-17:00	**Session C: Ground support and operations for interplanetary small satellite missions** *Session Chairs: K. Angkasa and M. Saing*

	C.1 DSN's Emergency Control Complex *(S. Nabhan)* C.2 NASA Affiliated Deep Space Station 17: IM-2 Mission Support and Beyond *(B. Malphrus)* C.3 Accounting for Orbital Long-Duration Eclipses for Lunar Trailblazer Mission Operations *(M. Anvelt)* C.4 A First-in-Flight Demonstration of the Deep Space Network's Multiple Uplinks Per Antenna Capability *(Z. Towfic)* C.5 Automated Planning, Logistics, and Learned Operations (APOLLO) Software for Lunar Base Operations *(S. Muniyasami)*
17:00-17:30	**Session C Q&A Panel: K. Angkasa and M. Saing**
17:30-17:40	**Day 1 Closing Remarks: A. Babuscia**
17:40-20:00	Dinner

Wednesday, April 30th , 2025

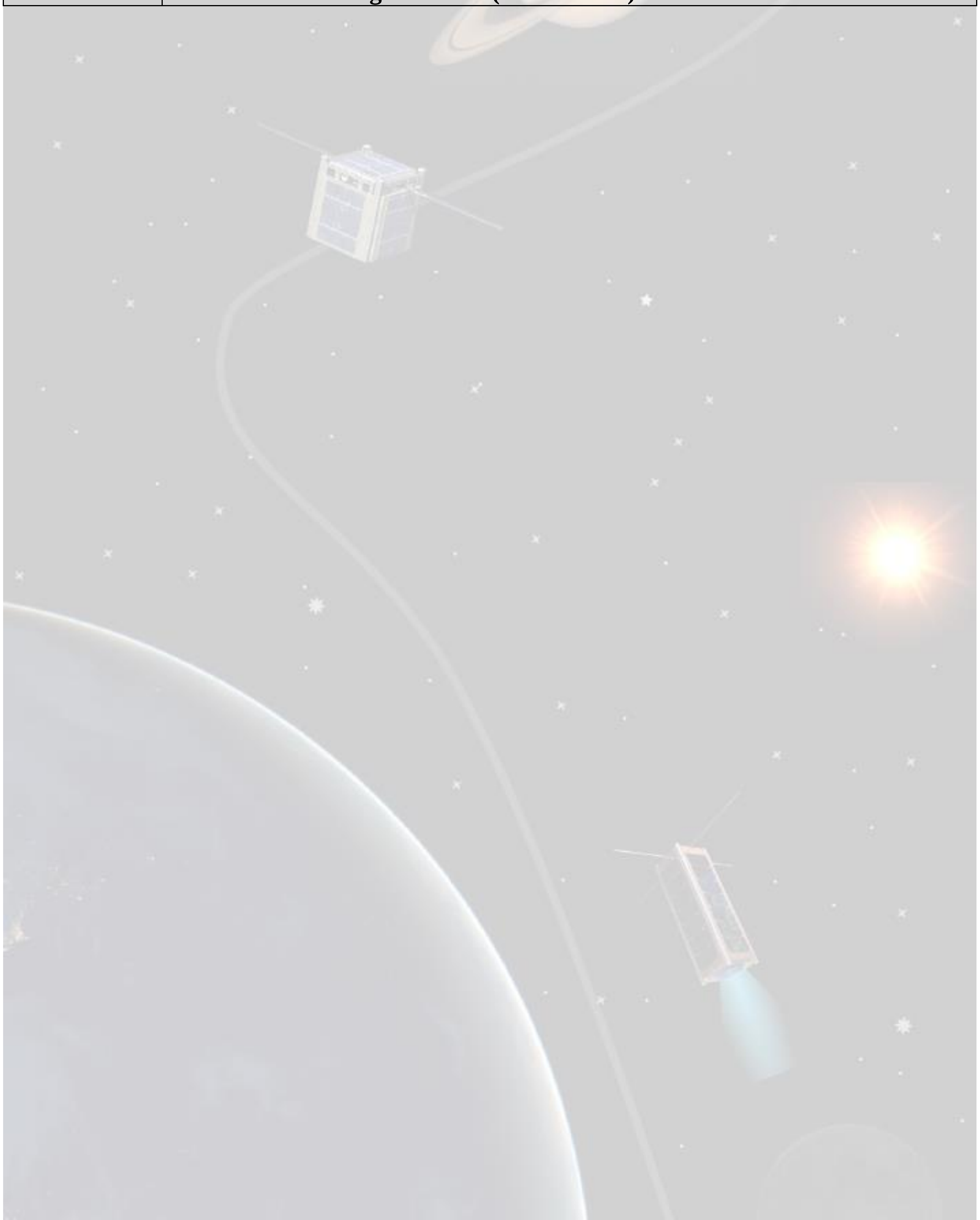
Time (PDT)	Event
7:30-8:45	Registration and Breakfast
8:45-9:00	**Opening Remarks (A. Babuscia)**
9:00-10:00	**Keynote Speaker: Dr Cynthia Phillips (Jet Propulsion Laboratory)** **Europa Clipper** *Moderator: M. Saing*
10:00-10:30	Coffee break
10:30-11:45	**Session D: Solar Sails, Propulsion, Launch and Transfer Technologies for Interplanetary Missions** *Session Chairs: M. Saing and A. Guarneros Luna*
	D.1 Kirigami/Origami Actuators for Solar Sail Attitude Control *(H. Jo)* D.2 Impulse Space: Pioneering Low-Cost Paths to GEO and Deep Space *(P. Shaw)* D.3 The Solar Sail Racing Championship: Advancing Interplanetary Propulsion Through Competition *(J. McGrath)* D.4 Micro-Mirror Arrays for Solar Sail Attitude Control *(M. Hossain)* D.5 Responsive Access to Cislunar Space Enabled by Rideshare-Compatible Orbit Transfer Vehicles *(M. Loucks)*
11:45-12:15	**Session D Q&A Panel: M. Saing and A. Guarneros Luna**
12:15-13:15	Lunch
13:15-14:15	**Session E: Instrumentation and technologies for interplanetary missions** *Session Chairs: J. Thangavelautham and C. Lau*
	E.1 Mars InfraRed Compact Atmospheric Temperature Sounder (MIRCATS) *(T. Pagano)* E.2 SmallSats with Wheels: A Discussion of the V&V Approach for the Cooperative Autonomous Distributed Robotic Exploration (CADRE) Mission *(C. Smith)* E.3 Development of a ruggedized rubidium CPT clock platform *(W. Krzewick)* E.4 Quadruped Robots for Extreme Terrain: Bridging Mobility Challenges through Bio-Inspired Innovation *(V. Gowri)*
14:15-14:45	**Session E Q&A Panel: J. Thangavelautham and C. Lau**

14:45-15:30	Travel from Caltech to JPL (transportation not provided), check in at visitor center
15:30-17:30	**JPL Tour**
17:30-18:00	JPL Check out and travel back to Caltech (transportation not provided)
18:00-20:00	Dinner

Thursday, May 1st, 2025

Time (PDT)	**Event**
7:30-8:45	Registration and Breakfast
8:45-9:00	**Opening Remarks (A. Babuscia)**
9:00-10:00	**Keynote Speaker: Dr Sabrina Feldman (Jet Propulsion Laboratory)** **Next-Generation SmallSats: Revolutionizing Planetary Exploration** *Moderator: A. Babuscia*
10:00-10:30	Coffee break
10:30:12:00	**Session F: Innovative concepts for interplanetary missions** *Session Chairs: A. Babuscia and A. Guarneros Luna*
	F.1 ESCAPADE's Journey: Lessons Learned for low-cost Planetary Missions *(R. Lillis)* F.2 Opportunistic System Design for Temporary Moon Exploration from Geosynchronous Orbit *(L. Vance)* F.3 2029 Caltech Apophis Mission – ARGOTEC's CubeSats *(G. Saita)* F.4 Longevity in Space: The Space Song Foundation *(J. Christensen)* F.5 CATS-I: Reconfigurable CubeSat Swarm for (99942) Apophis 2029 Flyby *(H. Vernekar)* F.6 A Nano-Lander Concept for In-Situ Exploration of Titan's Hydrocarbon Lakes: A Hitch hike with Dragonfly *(H. Thukral)*
12:00-12:30	**Session F Q&A Panel: A. Babuscia and A. Guarneros Luna**
12:30-13:30	Lunch
13:30-14:30	**Keynote Speaker: Justin Kugler (Intuitive Machines)** **Intuitive Machines** *Moderator: J. Thangavelautham*
14:30-15:00	Coffee break
15:00-16:30	**Session G: Attitude Control, GNC, SMART and radiometric technologies for interplanetary small satellite missions** *Session Chairs: K. Angkasa and C. Lee*
	G.1 Metasurfaces for sunlight steering: a tool for satellite attitude control and communications *(T. Joly-Jehenne)* G.2 An Updated Parametric Design of a Torsion Pendulum to Demonstrate Attitude Control Using Microoptoelectromechanical System Control of Radiation Pressure *(J. Messer)* G.3 Solving Momentum Management in the Martian Atmosphere *(A. Bichara)* G.4 CubeSat Interplanetary Exploration *(O. Belian)* G.5 Advancing SMART Devices Ecosystem to Accelerate Lunar and Martian Surface Exploration and Development *(J. Thangavelautham)*

	G.6 SmallSat Orbit Determination Using Onboard One-Way Radiometric Tracking And Atomic Clock *(T. Ely)*
16:30-17:00	**Session G Q&A Panel: K. Angkasa and C. Lee**
17:00-17:10	**Conference Closing Remarks (A. Babuscia)**



Welcome

Welcome to the 2025 Interplanetary Small Satellite Conference (ISSC), which will address the technical challenges, mission concepts, mission operations, and practicalities of space exploration with small satellites. This conference is organized by an evolving group of students, alumni, and staff from Caltech, NASA's Jet Propulsion Laboratory, the SpaceTreX Laboratory at University of Arizona, Oligo, and Lockheed Martin. The scope of ISSC is slightly broader than CubeSats only and it includes interplanetary small satellite missions or vehicles that do not fit into the CubeSat standard. This allows the conference to incorporate an important segment of the community, and to encourage the "outside the box" thinking that is critical to future interplanetary small satellite missions. Thank you for joining us in Caltech

— *The Organizing Committee*

Registration Hours and Contact Information

The registration desk will open from 7:30 am to 3pm on April 29th , April 30th and May 1st. If you have any questions during the conference, please don't hesitate to contact the organizing committee at info@intersmallsatconference.org at any time during the conference.

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 a Telecommunication Product Delivery Manager (PDM) at NASA JPL (337K). Currently, she is the telecom PDM for VERITAS mission, telecom lead for PRIMA mission concept, and involved in numerous early concepts and proposals. In the small satellite domain, she leads the telecommunication efforts at TeamXc. Previously, she has been a telecommunication system engineer for Mars 2020, telecommunication lead for LunaH-Map, BioSentinel, ASTERIA and RainCube missions at JPL, and PI for the Inflatable antenna for CubeSat effort. Before JPL, she has worked as a postdoctoral researcher and teaching assistant at MIT where she developed communication systems for different university missions (CASTOR, ExoplanetSat, Ter- Sat, REXIS, TALARIS).

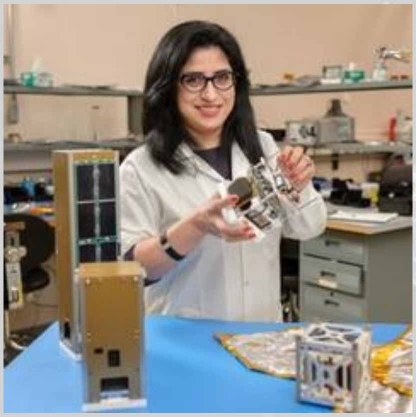
Her current research interests include communication architecture design, statistical risk estimation, multidisciplinary design optimization, and mission scheduling and planning. She is a founding member for ISSC since its first edition at MIT in 2012 (formerly known as iCubeSat), and she is a session 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.

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, MSL, M2020 and VERITAS. 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.



Ali Guarneros Luna is a Senior Space Architect at Lockheed Martin (LM). Before joining LM, she worked at NASA Ames Research Center in the Programs and Projects Management Division, specifically within the STMD Small Satellite Technology Program, where she managed the Tipping Points and ACOs, among other program initiatives. At NASA, she also contributed to the Office of System Safety & Mission Assurance (SS&MA) and the Office of Engineering Directorate, serving as a technical authority for small satellite development and payloads bound for the International Space Station (ISS).
In the Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) National Lab, Ali worked as a system and safety engineer. As part of the Edison Program, she played a key role in systems engineering, mission and ground operations, and launch vehicle services for multiple CubeSat projects, including the Technological and Educational Nanosatellite (TechEdSat). She also served as Deputy Project Manager, ISS expert, and launch vehicle interface for the Small Spacecraft Technology (SST) program's NODES project. Additionally, in the Sub-Orbital Aerodynamic Re-entry EXperiments (SOAREX) Series, Ali took on multiple engineering roles, including design, building, and testing.
Since 2019, Ali has been working as a part-time professor at San Jose State University.

Michael Saing is a Systems Engineer in the Project Systems Engineering and Formulation Section at the Jet Propulsion Laboratory (JPL). He is in the System Model, Analysis, and Architecture group and is a subject matter expert in space mission cost estimation and small satellites systems engineering. He is also one of the subsystem's engineer chair
for JPL's Foundry elite concurrent engineering design teams - TeamX, TeamXc, and ATeam.
Michael is also tasked by NASA Headquarters as a proposal reviewer, small satellites/ cubesats data collection, and model development. He graduated with an Aerospace Engineering degree (B.S.) from CSU Long Beach. After graduation, he started his early career work at the NASA Ames Research Center in Mountain View, CA

prior to joining JPL. As an amateur backyard astronomer, his interests and hobbies are in the areas of astrophysics and heliophysics science, astrophotography, and telescopes.

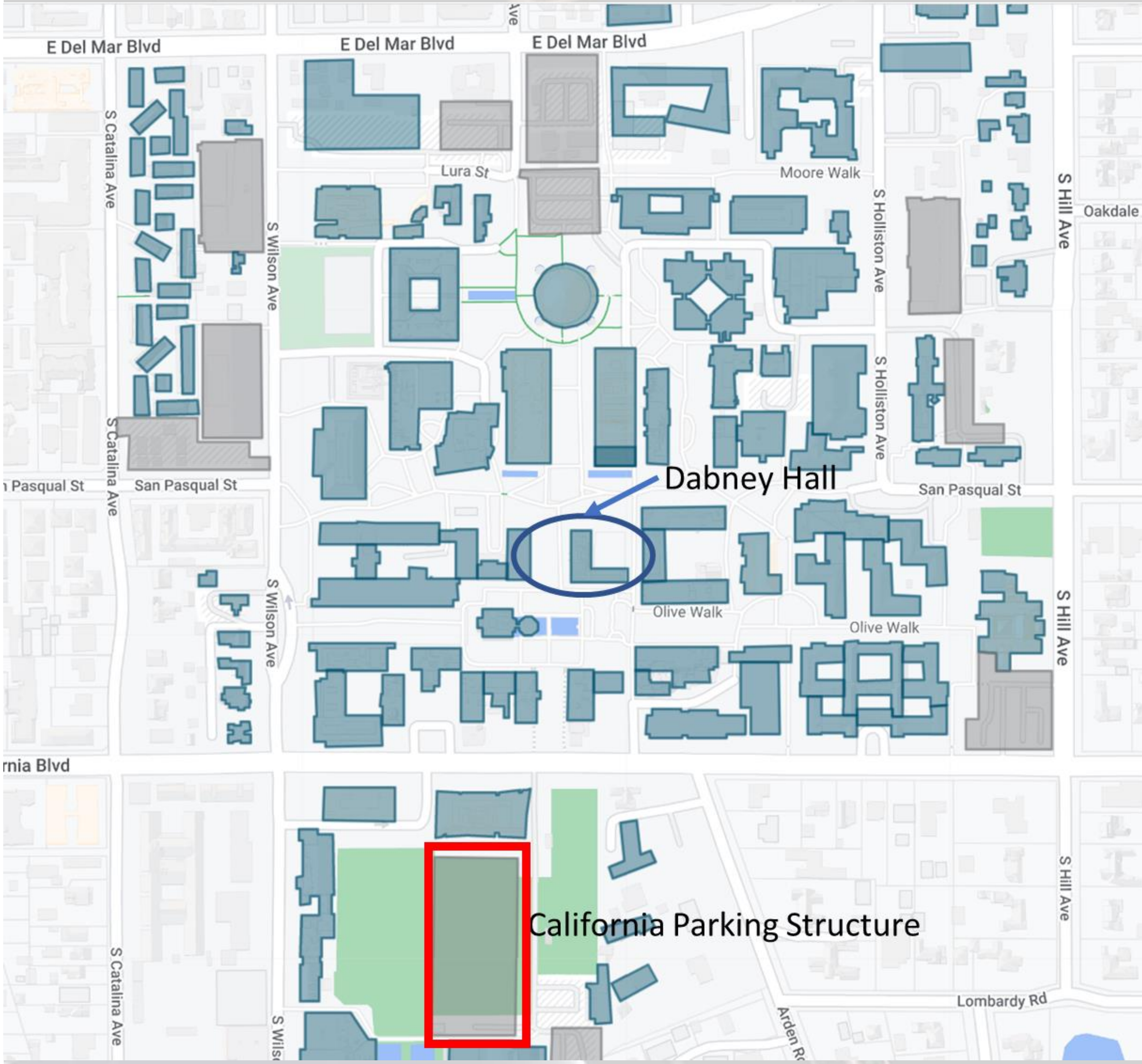
Kris Angkasa is a Program Area Manager at Jet Propulsion Laboratory in the Interplanetary Network Directorate (IND), home of the NASA's Deep Space Network (DSN) and Multi-mission Ground Systems & Services (MGSS) programs.
She has over 30 years of experience in space exploration, focusing her work in the DSN & space communication systems. Her efforts in the space industry include the development of a Ka-band TT&C subsystem for a commercial satellite at the Hughes Space & Communications. At JPL, her work includes the design, implementation, and testing of the DSN Block V Receiver and Flight Radios (SDST, Electra, Iris) for the flagship missions (Kepler, MER, MRO, MSL, Juno, MAVEN, and Mars 2020) as well as, the secondary payload CubeSats onboard Artemis I. Kris holds an MS degree in Electrical Engineering from the University of Southern California and a BS degree in Computer Science from the California Polytechnic University, Pomona.

Jekan Thanga has a background in aerospace engineering from the University of Toronto. He worked on Canadarm, Canadarm 2, and the DARPA Orbital Express missions at MDA Space Missions. Jekan obtained his Ph.D. in space robotics at the University of Toronto Institute for Aerospace Studies (UTIAS) and did his postdoctoral training at MIT's Field and Space Robotics Laboratory (FSRL). Jekan Thanga is an Associate Professor and heads the Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory and the NASA-funded ASTEROID (Asteroid Science, Technology and Exploration Research Organized by Inclusive eDucation) Center in Formation at the University of Arizona. He has been an advocate and leader in implementing Diversity, Equity and Inclusion programs in aerospace research, with nearly 300 graduate and undergraduate students matriculating through those programs. Jekan and his team of students have co-authored nearly 200 technical publications. He is the Engineering Principal Investigator on the AOSAT I CubeSat Centrifuge mission. He and his team of students were winners of the Popular Mechanics Breakthrough Award in 2016 for proposing the SunCube FemtoSat and won a Best Paper Presentation Award at AMOS 2019 for the Early Warning Constellation to Detect Incoming Meteor Threats. Jekan and his team of students were finalists for the NASA 2020 BIG Competition and winners of the 2021 NASA RASCAL Competition.

Kris Buckmaster is a Mission Interface Manager supporting NASA's Deep Space Network and Multimission Ground System and Services programs. After receiving a BS degree in Engineering Physics from Westmont College, he started his career in deep space tracking and communications in 2003, working on the operations and maintenance contract for the Deep Space Network doing critical events planning and operations engineering. Kris joined JPL in 2014 as a software systems engineer, focusing on ground data systems and provisioning CCSDS Space Link Extension services. He also worked as a systems engineer for NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC) for Tools and Services to make NASA's ocean and climate data accessible and meaningful. These days, he's sharpening his project management skills and enjoys applying agile software development practices to his work supporting a portfolio of missions that include both flagships like Europa Clipper, and cubesats like Lunar Flashlight.

Location, Venue, Parking, Covid-19 and Wifi Information

The conference will be at the Dabney Hall in Caltech, Pasadena. There are several parking structures around Caltech. The closest one is the California Parking structure highlighted in red in the map.



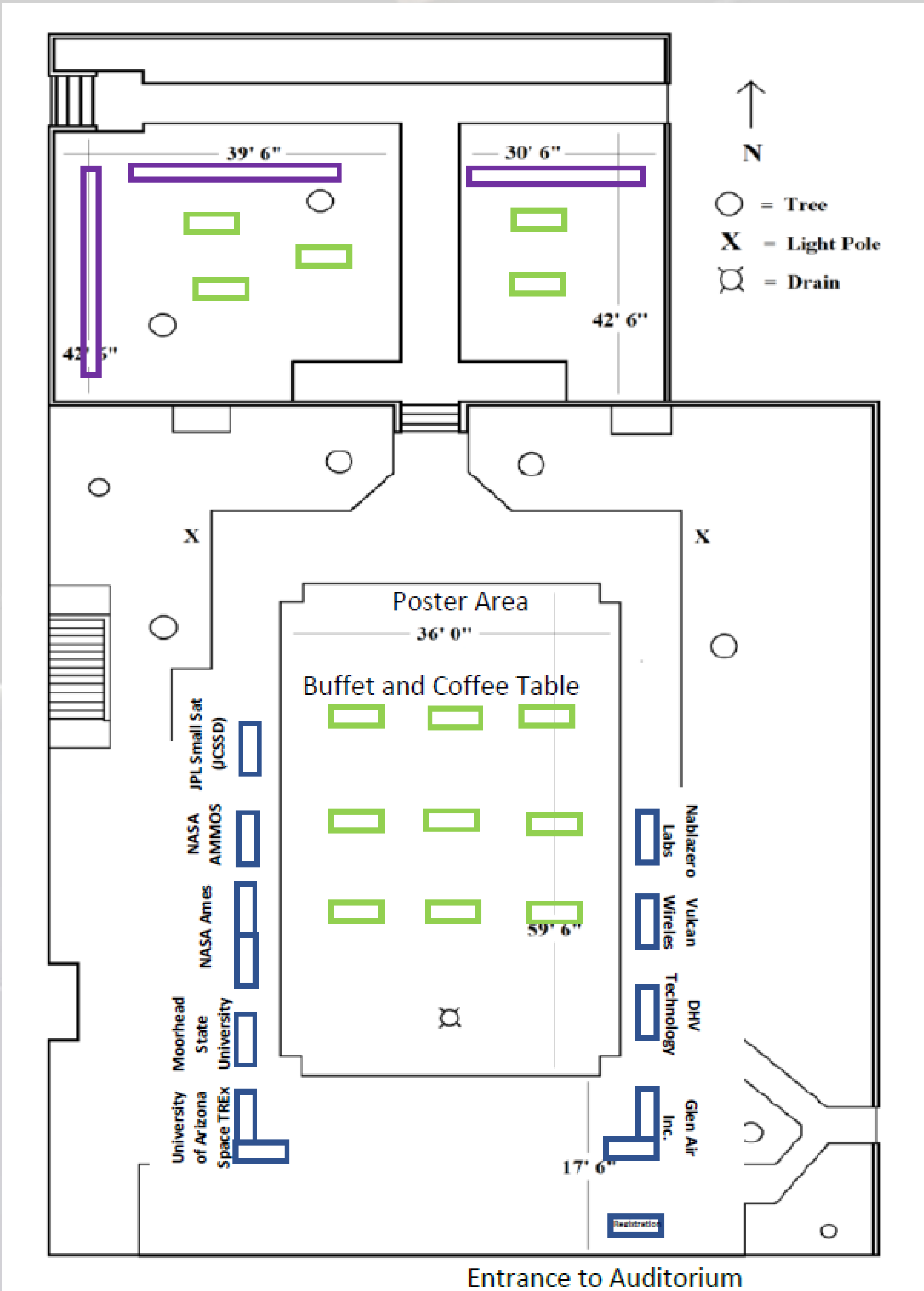
Parking permit can be payed directly at the pay stations. More information can be found: https://parking.caltech.edu/parking-info/visitor-parking

There are no COVID restrictions on Caltech campus at the time of printing this booklet. The conference organizers will post any changes to COVID-related policies to the ISSC website.

There will be a specific Wifi network setup at the conference. Password will be provided on site.

Registration Area, Conference Hall, Exhibitors and Meals Area Map

A rough map of the conference venue with exhibitors' tables and booths is shown below. Meals will be provided in the same exhibitors' courtyard.



Keynote Speaker Biographies

Dr. Leon Alkalai

Mandala Space Ventures

Leon Alkalai is a retired Technical Fellow of the NASA Jet Propulsion Laboratory (JPL), California Institute of Technology where he spent 32 years after getting his PhD at UCLA in 1989. During his career at JPL, Dr. Alkalai held numerous leadership positions and was responsible for the capture leadership of both the GRAIL mission to the Moon (2007) and the INSIGHT lander on Mars (2012). For both efforts, Dr. Leon Alkalai received Distinguished Individual Achievement medals from NASA in 2011 and 2019 respectively. Dr. Alkalai was also heading up JPL strategic partnerships and strategic planning for the Laboratory. In early 2021, Dr. Alkalai retired from JPL and created Mandala Space Ventures, a space-focused, Pasadena-based incubator for new start-ups in the emerging space economy. Leon is also the General Partner at the Explorer-1 Venture Fund which is also affiliated with the Mandala space incubator. Mandala launched its first new venture called Continuum Space Systems, a Software as a Service (SaaS) company for the emerging digital space economy. Mandala has two other portfolio companies in the studio; Viridian Space Corporation and Specter Aerospace. Mandala has also recently launched Sophia Space Inc., which is developing data centers in space.

Dr. Cynthia Phillips

Jet Propulsion Laboratory, California Institute of Technology

Dr. Cynthia Phillips is a planetary geologist at the NASA Jet Propulsion Laboratory in Pasadena, CA. She currently works on the Europa Clipper mission, where she serves as a Project Staff Scientist among other roles, in addition to being Project Scientist on a New Frontiers mission concept proposal. Dr. Phillips received her undergraduate degree in astrophysics from Harvard, and her PhD in Planetary Science from the University of Arizona. She spent 15 years at the SETI Institute and NASA Ames Research Center before joining JPL in 2015. Dr. Phillips is an expert in scientific image processing and small-scale surface processes on planetary satellites, with a particular focus on Europa, Io, and Enceladus.

Dr. Sabrina Feldman

Jet Propulsion Laboratory, California Institute of Technology

Dr. Sabrina Feldman is the Program Manager for JPL's Planetary Science Formulation Office in the Planetary Science Directorate. She joined JPL in 1997 as a member of the In Situ Exploration Technologies group after earning her Ph.D. in physics from U.C. Berkeley, where her research focused on astrophysics detector development. With over sixteen years of experience in formulation leadership roles, she has served as Program Manager for the Planetary Science Instruments Office, Deputy Program Manager for the Earth Science Research and Mission Formulation Office, Program Manager for the Earth System Explorer Office, and Assistant Science Division Manager for Formulation and Technology. Her background also includes roles as a Physical Scientist at NASA Ames Research Center and as an Assistant Professor of Physics at the University of Puget Sound. Sabrina is passionate about helping teams to develop innovative planetary mission and instrument concepts that address fundamental questions about our solar system.

Justin Kugler

Intuitive Machines

Justin Kugler is an experienced aerospace professional currently serving as the Director of Business Development at Intuitive Machines, focusing on strategic partnerships for cislunar infrastructure. Previously, Kugler founded Cosmosynth, providing consulting services in aerospace business development, and held various leadership roles at Redwire Space, including General Manager for In-Space Manufacturing & Operations and Vice President for Civil & Commercial Space. Prior experience includes Vice President of Advanced Programs & Concepts at Made In Space, Commercial Innovation Manager at CASIS, and engineer roles at SAIC, L-3 Communications, the Central Intelligence Agency, and NASA Johnson Space Center. Kugler holds a B.S. in Aerospace Engineering from Texas A&M University, an M.S. in Mechanical Engineering from Rice University, and a certificate in Strategic Foresight from the University of Houston.

Conference Abstracts

K.1 Navigating the Emerging Commercial Space Ecosystem

Leon Alkalai
(Mandala Space Ventures)

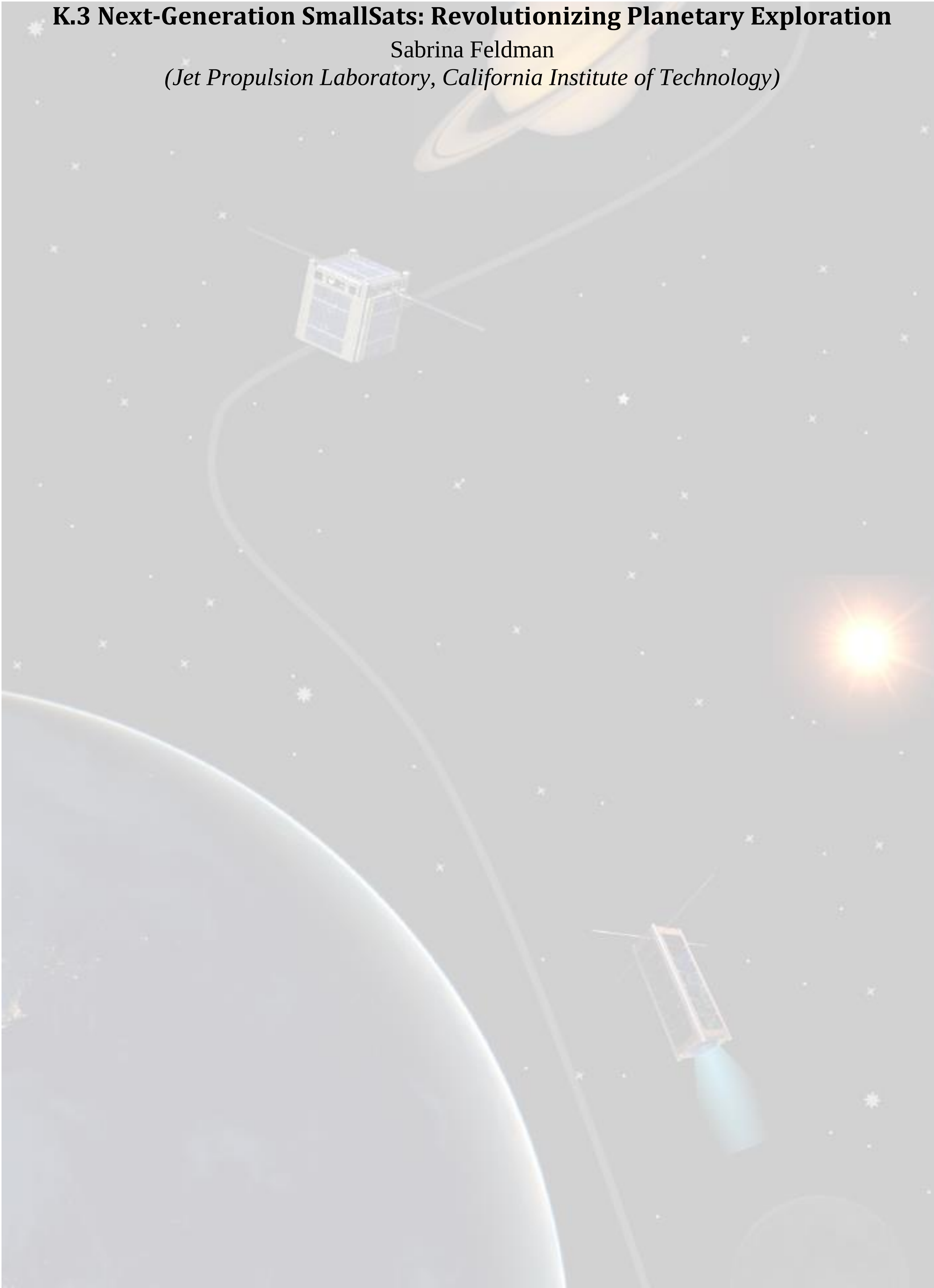
K.2 Europa Clipper

Cynthia Phillips
(Jet Propulsion Laboratory, California Institute of Technology)

The Europa Clipper mission, NASA's flagship mission to investigate Jupiter's ocean moon Europa, launched on October 14th, 2024. This mission will study the habitability of Europa - this fascinating moon, about the size of Earth's moon, has a vast ocean of liquid water underneath its icy surface and could be one of the best places in the solar system to search for life beyond the Earth. Europa Clipper's payload of 10 science investigations includes imagers ranging from the UV to the thermal IR, plus a radar, dust and gas analyzers, a magnetometer and plasma instrument, and a gravity experiment. The mission will investigate Europa's geology, ice shell and ocean, composition, and interior, looking for places below Europa's surface that could support life as we know it. Europa Clipper had a successful Mars flyby on March 1st, and is heading back to Earth for a gravity assist in December of 2026 to help speed the spacecraft on its way out to the Jupiter system, where it will arrive in 2030.

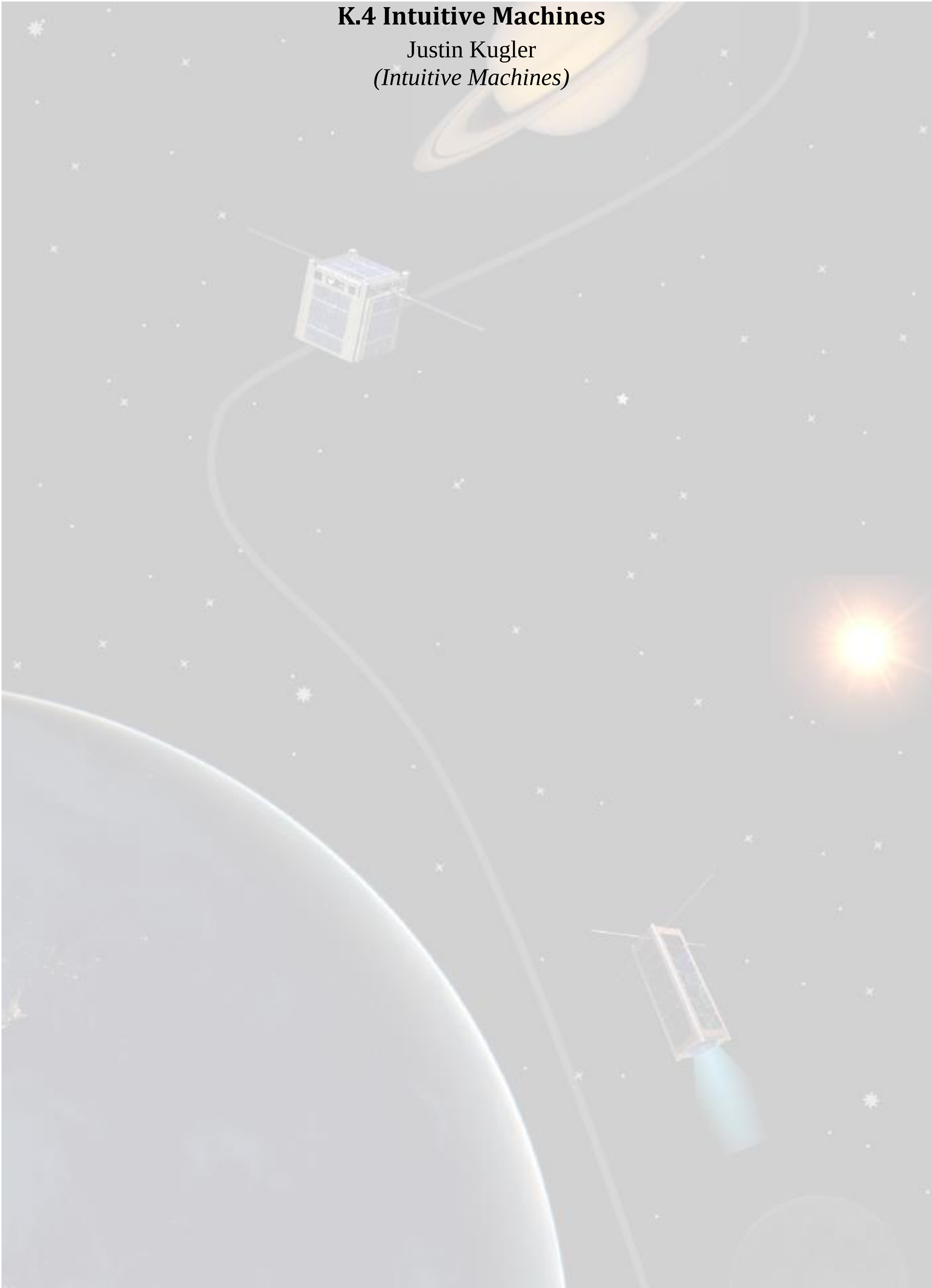
K.3 Next-Generation SmallSats: Revolutionizing Planetary Exploration

Sabrina Feldman
(Jet Propulsion Laboratory, California Institute of Technology)



K.4 Intuitive Machines

Justin Kugler
(Intuitive Machines)



A.1 ESA Interplanetary Small Spacecraft Missions: Pushing the Boundaries of Miniaturized Systems & Technologies

Simone Simonetti, Roger Walker
(European Space Agency (ESA))

The European Space Agency (ESA) is enhancing its small spacecraft capabilities, enabling rapid development of missions across the inner solar system. These missions represent a significant step forward in cost-effective interplanetary and lunar exploration, promoting pioneering innovation and paving the way for further advancements.

Various ESA programs have ambitious projects and enabling technology development activities to facilitate these objectives. Various mission profiles are under development, including lunar orbiters, NEO rendezvous, and missions to Mars. CubeSats are integral to larger missions, such as the Hera mission, currently en route to the Didymos binary asteroid system, and the Ramses mission under development to rendezvous with asteroid Apophis before its close encounter with Earth in 2029.

Several key interplanetary and lunar SmallSat missions are in definition or development phases:

- Milani: Equipped with a hyperspectral imager, Milani will perform detailed spectral imaging of the asteroid Dimorphos to analyze its surface composition.

- Juventas: Using a low-frequency radar, Juventas will characterize the gravity field and internal structure of Dimorphos, providing insights into its subsurface composition.

- LUMIO (Lunar Meteoroid Impacts Observer): This stand-alone 12U CubeSat will observe lunar meteoroid impacts from the Earth-Moon L2 Lagrangian point, capturing flashes of light from impacts and providing data on the lunar meteoroid environment.

- HENON (HEliosphoNeer for sOlar and interplanetary threats defeNce): Maneuvering to and operating in a distant retrograde orbit, the stand-alone HENON 12U CubeSat will showcase advanced SmallSat capabilities for autonomous deep-space missions, serving as a precursor for more complex interplanetary missions such as adverse space weather advance warning services.

- SATIS: Focused on NEO rendezvous, SATIS will demonstrate a cost-effective rapid reconnaissance capability for observing potentially hazardous asteroids.

- VMMO (Lunar Volatile and Mineralogy Mapping Orbiter): This 16U CubeSat will map the distribution of water-ice and ilmenite on the lunar surface using a multi-wavelength Chemical Lidar system.

- Small Missions for Moon Exploration: This activity includes pre-phase A studies of SmallSats and small surface missions for scientific and technological exploration of the moon.

- Low-Cost Mars Platforms: This activity identifies SmallSat and CubeSat platforms to be secondary passengers on LightShip, the new European propulsive tug under development. LightShip will transfer spacecraft to Mars, enter Mars orbit, and host MARCONI for data relay services.

ESA works closely with European industry to develop key technologies such as compact high performance deep-space transponders for reliable communication, propulsion systems optimized for SmallSat applications, and radiation-tolerant avionics. These missions and associated technological advancements underline the significant potential of SmallSats and CubeSats to contribute to our understanding of the solar system and space weather. They serve as cost-effective, agile platforms supporting future scientific discovery, planetary defense and exploration endeavors, shaping future interplanetary SmallSat initiatives and fostering international collaboration.

A.2 CAPSTONE’s Mission Extension: Navigating the Future of Cislunar Technology

Thomas Gardner*, Alec Forsman*, Anthony Zara*, Rebecca Rogers*, Nathan Re*, Hannah Umansky**

*(*Advanced Space, LLC, **Terran Orbital)*

Launched in late June 2022, the Cislunar Autonomous Position System Technology, Operations, and Navigation Experiment (CAPSTONE) has been operating in the Earth-Moon, Southern L2 Near Rectilinear Halo Orbit (NRHO) for more than two years. After successfully completing its primary mission objectives, CAPSTONE was awarded a 15-month mission extension in September of 2024. The goal of this extension was to continue to use CAPSTONE to provide valuable and informative data to the NASA Gateway program and leverage the platform to raise the TRL of several cislunar technologies. This presentation presents an analysis of the operational data obtained throughout the mission, including navigation performance, maneuver strategies, and results of the Cislunar Autonomous Positioning System (CAPS), and overviews the ongoing onboard technology demonstrations.

Prior to the CAPSTONE spacecraft’s launch, Advanced Space conducted a series of analyses to quantify expected navigation and maneuver performance and to qualify the different methodologies, which have been used to operate CAPSTONE in the NRHO. This presentation presents a retrospective analysis that quantifies the as-flown operations performance in comparison to pre-flight expectations and highlights how these operational strategies have been adapted and used to support the NASA Gateway team. Additionally, a characterization of the CAPS performance will be described. These ongoing experiments involve the spacecraft communicating using a two-way, coherent signal to obtain range and Doppler navigation measurements that can be processed onboard for absolute state estimation. This study characterizes the results of crosslink experiments to date. Analyses showing potential performance of future iterations of crosslink navigation using CAPS are also highlighted to preview a path forward for autonomous deep-space navigation.

Finally, the mission extension technology demonstrations focused on spacecraft autonomy and navigation will be briefed. A focus will be placed on the concept of navigating a spacecraft in the cislunar regime using optical measurements derived from the Moon’s horizon and demonstrate the effectiveness of these techniques using real imagery from the CAPSTONE spacecraft. Generated optical-only orbit determination solutions for CAPSTONE are presented and demonstrate the possibility of autonomously navigating the spacecraft, as well as potential future space vehicles, such as NASA’s planned Gateway space station, in the NRHO.

By continuing operations, CAPSTONE provides a low-cost, high-impact opportunity to refine critical technologies for upcoming lunar missions, contributing to the broader goals of NASA, commercial lunar initiatives, and commercial partners in cislunar space.

A.3 Designing and Producing interplanetary spacecraft resilient to requirements evolution

Christophe Mandy
(Rocket Lab)

Rocket Lab has built two spacecraft for UC Berkeley’s Space Sciences Laboratory for the NASA Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE) mission to Mars. The mission will place two spacecraft in Mars orbit to understand the structure, composition, variability, and dynamics of Mars' unique hybrid magnetosphere, demonstrating Decadal-class small spacecraft capabilities for Mars. This paper will discuss the ESCAPADE spacecraft concept of operations and the flexible development cycle which allowed the design to proceed well past CDR while staying agnostic to launch vehicle and ultimate trajectory. We will focusing in particular on trajectory margining, design flexibility and production processes to allow for rapid late-stage design or requirement changes. Applications of the approach to other Rocket Lab spacecraft will be touched on as well, including the Rocket Lab Mission to Venus.

A.4 Chimera-1: Accelerated Custom Platforms for Space

Jacob Rodriguez, Alton Zhang, Evan Tars, Charles Naff-Rhymer, Carlyn Lee, Kaiy Muhammad
(Oligo Space)

As space technology advances, the need for cost-effective, rapidly deployable, and adaptable satellite solutions continues to grow. Oligo Space is addressing this challenge with Chimera-1, our multi-hosted payload satellite platform custom-tailored to lower barriers to orbit for commercial, research, and defense applications.

In this talk, we will introduce Oligo's mission and vision, highlighting our ongoing exploration of open source technologies like F prime and SatCat5 to enable software modularity and payload integration. Our approach emphasizes scalability, rapid deployment, and customer-driven mission customization, making space more accessible. We will also share insights from our industry engagements across the U.S., Europe, and Asia-Pacific and discuss how Chimera-1 is set to disrupt traditional satellite development cycles. With our first launch scheduled for October 2025, this talk will provide a discussion of the challenges, techniques, and opportunities in next-generation satellite deployment. We welcome any collaboration and discussion on how Chimera-1 can support diverse mission needs in the evolving space ecosystem.

A.5 The role of Small Satellites in Asteroid studies and Planetary Defense missions: the Hera Milani and Ramses CubeSat 1

M. Cardi*, M. Pavoni*, D. Calvi*, F. Parigi*, A. Zanotti*, E. Sanguineti*, F. Perez Lissi**, P. Martino**, I. Carnelli**, Milani Consortium member and partners***, RAMSES CubeSat 1 Consortium members and partners****

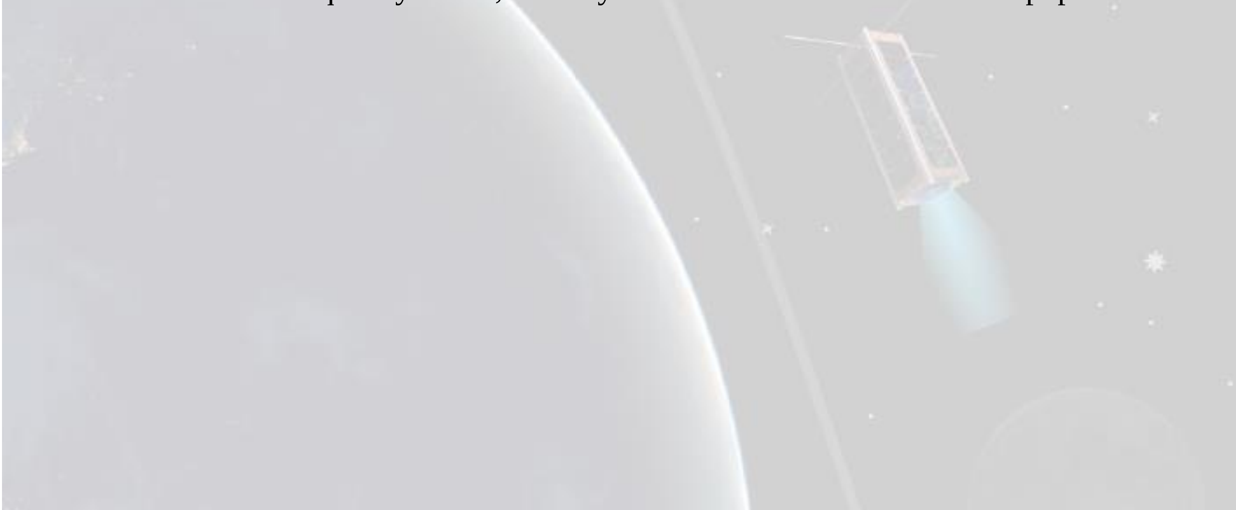
*(*Tyvak International Srl., **European Space Agency, *** Politecnico di Milano, Politecnico di Torino, Centro Italiano Richerche Aerospaziali, Altec Space, VTT, Huld, Kuva Space, Brno University of Technology, University of Helsinki, Institute of Geology of the Czech Academy of Sciences, Istituto Nazionale di Astrofisica, Technology for Propulsion and Innovation, **** Politecnico di Milano, Politecnico di Torino, Huld, EmTronIx, Astronika, IPAG - Institut de Planétologie et d'Astrophysique de Grenoble, Technical University of Dresden, Istituto Nazionale di Astrofisica, Technology for Propulsion and Innovation)*

In the frame of the last 20 years, the scientific community and space Agencies focused attention and addressed efforts on the asteroid analysis domain, in support of the Planetary Defence roadmap definition and implementation. The role of industry is crucial to develop and implement ground and space systems that can support the activities defined by such institutions and Government, and the collaboration between countries is necessary to fulfill such challenging objectives.

Tyvak International, a European Company leader in the small satellites’ development, launch and operations, plays an important role in the European planetary defence domain, being part of the first ESA’s planetary defence missions: Hera and RAMSES.

Hera was launched in 2024 to characterize the Didymos asteroid after NASA’s DART impact and currently on its way to the asteroid, while RAMSES, is the ESA mission to the Apophis asteroid, in the frame of the close encounter of April 2029. Both missions include two CubeSat’s each. Tyvak International is Prime Contractor of the development of the Hera Milani CubeSat, leading an European consortium of 10+ entities, and thanks to the experience gained through this mission and related heritage, was selected by ESA for the development of one of the RAMSES CubeSat.

Hera Milani will use a hyperspectral imager, an RGB camera and a dust analyser, to characterize the Didymos asteroid system; RAMSES CubeSat will implement the Milani platform to accommodate a Low Frequency Radar, to analyse the internal structure of the Apophis asteroid.



A.6 BioSentinel Mission Update: Two Years and Counting in Deep Space

Jesse Fusco, Matt Napoli
(NASA Ames Research Center)

BioSentinel has achieved unprecedented performance for a CubeSat in deep space with over two years of flight time. Following the conclusion of the primary science mission in April 2023, the Linear Energy Transfer (LET) Spectrometer has continued to collect solar and galactic radiation data from its unique location in heliocentric orbit. As well as the free space dataset offered by the BioSentinel LET is a valuable source of data for both model validation and future mission planning. As the spacecraft travels farther from Earth it is poised to provide longitudinally distributed measurements of solar particle events during solar maximum. Flight heritage has now been gained on many of the novel spacecraft components. The spacecraft bus continues to operate within the design envelope. The 3D-printed cold gas propulsion system provides momentum unloading from the reaction wheels. The power system has maintained power positive levels during flight. The IRIS radio communicates on a weekly basis with the Deep Space Network (DSN). Furthermore, the use of the software defined IRIS radio has given the mission the opportunity to help DSN verify several new features with a spacecraft in orbit. The extended mission operations are allowing the team to characterize the performance of the spacecraft components over longer durations of operations. NASA Ames led development of the BioSentinel spacecraft and mission operations. The novel subsystems and COTS components that comprise the BioSentinel bus can serve as a template for future deep space missions. With over 2 years of continuous operations, the data will inform the next generation of interplanetary Smallsat missions.

B.1 CubeSat enabled Differential Absorption Radar for Lunar water mapping

Aman Chandra, Christopher Walker
(University of Arizona)

Observations of the Moon from recent missions such as the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA) have independently detected widespread hydration on the lunar surface. Analysis of spectral signatures confirm molecular water in abundances ranging from 100 – 400 $\mu g\,g^{-1}$ H_2O. The University of Arizona is developing a Ka-band chirp radar system with an integrated 2.5- meter inflatable membrane deployable reflector. The payload packages in a 3U volume making it a suitable payload for deployment from a 12U CubeSat. This system has the potential to provide a game changing ~ 10 cm vertical and < 2 km cross range resolution thus enabling 3-D mapping of water on the lunar surface. The 12U spacecraft design also includes a passive radiometer for independent water line detection using limb sounding against the sun. The mission named LunaCat has been proposed to NASA’s 2024 CSLI program and derives heavily from the CatSat 6U inflatable antenna program currently operational in LEO. LunaCat’s launch is nominally planned for early-mid 2027 with a 2 year mission lifetime including 1 year science operations phase.

B.2 The UST-Lite Radio: A multi-channel software-defined transponder for spacecraft and surface assets at the Moon, Mars, and beyond

Dennis Ogbe, Michael Kobayashi, Zaid Towfic, Mazen Shihabi, Carl Spurgers, Lindsay White
(Jet Propulsion Laboratory, California Institute of Technology)

The UST-Lite radio is the latest offering of the Universal Space Transponder (UST) product line of software-defined radios developed at the Jet Propulsion Laboratory. Featuring advanced high-speed direct-RF sampling data converters, it is capable of generating and demodulating signals of up to 100 Msps on up to four simultaneously operating full-duplex channels. Multi-Gsps transmit rates are possible with custom RF frontends. The UST-Lite features a modular design with different RF frontend options form the common S, X, and Ka bands, with a UHF band RF frontend currently in development.

Although size, weight, and power (SWaP) is higher than the CubeSat-class Iris radio, parts selection and electronic and packaging design choices make the UST-Lite suitable for missions with high-reliability requirements. The UST-Lite is applicable to interplanetary SmallSat missions, Lunar and Martian orbiting stations, as well as surface assets like rovers, landers, or other surface-based communication nodes.

In this presentation, we will give an overview of recent design improvements to the UST-Lite digital and RF subsystems with a focus on the recent development efforts for the Ka and UHF band RF modules. In addition, we will discuss conceptual studies of the UST-Lite as both a lunar orbital relay radio and as a surface radio. Although both of these applications have different requirements and constraints, the UST-Lite applies to both scenarios due to its modularity and flexibility.

The UST-Lite radio has undergone a successful technology transfer to an industry partner and is currently available for procurement.

B.3 The Arke Low SWaP Transponder for Mars and Lunar Missions

Nacer Chahat, Frank Chaqueco, Andrew Daniel, Brett Douglas, Gaurangi Gupta, Joshua Miller, Eleanor Naudzius, Carl Spurgers, Adrian Tang, Mark Taylor, Zaid Towfic
(Jet Propulsion Laboratory, California Institute of Technology)

The success of extremely low size, weight, and power (SWaP) limited missions such as the Ingenuity helicopter, and the development of new SWaP constrained missions like CADRE has driven the need for energy-efficient and compact transponders. For example, in the case of the Ingenuity helicopter, the lack of such transponder forced the helicopter to only support point-to-point links to the Perseverance (Mars 2020) rover, which possessed a surface-to-orbiter relay link back to Earth through the Mars Relay Network (MRN). This greatly constrained the mission in that the helicopter, while being extremely mobile, had to stay within a limited distance from Perseverance due to its limited surface link. To compound the issues, the surface link was further limited by the surrounding terrain and its negative effects on the signal.

In order to alleviate these limitations, JPL's Flight Telecommunication Section has undertaken the task of creating an energy-efficient compact transponder that would support communication to the MRN and the future lunar relay network. This allows surface assets to communicate with scalable power to orbiters, detaching these platforms from larger counterparts. The transponder is based on an efficient System-on-Chip (SoC) that implements the heritage Prox-1 protocol and interacts with the spacecraft avionics via Ethernet, among other interfaces. Additionally, the RF link is implemented via an RF Integrated Circuit (RFIC) that can perform the digital-to-RF conversion directly (and vice-versa). The prototype development is currently targeting 100x100mm, including path to Class B missions. Future iterations of this transponder seek to minimize size further to 85x55mm. The transponder is expected to draw < 12W DC while producing on the order of 2W RF at UHF (to support Mars missions) and 4W at S-band (to support lunar missions). Complementary antenna designs for UHF and S-bands are also considered in this development, to deliver a complete telecommunication system for direct-to-orbit capability for Mars and lunar landers/rover/aerobots.

B.4 Edge AI/ML Model Processing for Near-Earth and Deep Space Missions Using Qualcomm Snapdragon

Steven Doran
(Jet Propulsion Laboratory, California Institute of Technology)

The rapid proliferation of artificial intelligence (AI) and machine learning (ML) applications has driven demand for efficient, cost-effective, and low-power computational platforms capable of delivering high-performance modeling for near Earth and Deep Space missions. The traditional approach for spaced-based avionics is to implement processing hardware tailored for each mission. This method incurs significant costs and program overhead. However, advancements in edge computing and optimized deep learning frameworks have unlocked the potential of commercial off-the-shelf (COTS) processors that match or exceed the processing power of current avionics options with lower cost and power requirements. To leverage COTS hardware for future missions, a joint research venture between the Jet Propulsion Laboratory (JPL) / Caltech and Qualcomm was established to "provide funding for joint research in fault tolerant computer systems for mission critical space and automotive applications." This presentation highlights the current activities that resulted in the JPL / Qualcomm joint research efforts, including the deployment of the Mars Helicopter to the Martian Surface, to the development of Flight Software that executes complex Edge and Deep Learning models concurrently on multiple Qualcomm Snapdragon System On the Chip (SoC) processor. Radiation testing "at the beam" using Qualcomm's advanced testing facilities has demonstrated the Snapdragon processor is resistant to both Single and Double Event Upsets (SEU's) at levels a deep space mission is expected to encounter during its mission life. Finally, this presentation describes how the incorporation of JPL' s F' open-source Flight Software (FSW) Framework enabling rapid deployment of advanced Edge and Deep Learning AI/ML models with low overhead and Cybersecurity resiliency.

B.5 C-DST: a CubeSat platform for Deep-Space communication link

Giovanni Cucinella*, PierLuigi De Rubeis**, Lorenzo Simone**, Riccardo Di Zitti**, Dario Gelfusa**, Antonio Miraglia***

*(*IMT Srl., **Thales Alenia Space Italy TT&C product, ***European Space Agency)*

It is nowadays almost 25 years since that far 1999 when the first Cubesat satellite was launched. At that time, this revolutionary idea constituted the new frontier of the space application. This little satellites today are often used to provide ancillary functions for the scientific mission and are being used in commercial market as well, providing a useful extension of the main mission features and instruments. When DART mission has projected a satellite toward the Didymos asteroids, Cubesat satellites has provided the video of the moment after the impact, giving a fundamental contribution to the mission at a very low expanse.
To communicate, the cubesat satellite normally rely on the closest large or medium class satellite, which provides support for the near communication the cubesat are designed for.

On this field Italian companies (a partnership between IMT and TAS-I under European Space Agency contract – ESA) has developed the so-called C-DST (Cubesat Deep Space Transponder), a transponder capable of providing an earth-to-space direct link in X-band with deep space performance.

The C-DST shall equip a CubeSat-based platform to be deployed beyond LEO orbits and able to sustain deep
space condition.
The main challenge is represented by the lack of CubeSat standard equipment to be used for beyond-LEO orbit and for deep space application. Concerning the TT&C system perspective, this translates into the need to identify a specific architecture which allow to develop a TT&C system capable to:

- comply with the extreme miniaturization and low-power consumption requested by the CubeSat standard
- maintain the functionalities and performance usually requested to the TT&C for standard scientific mission
- provide the ground segment flexibility needed to reduce the launch and operation cost (i.e. allowing to catch piggybacking launch opportunities and optimizing the ground station use during the life).

The Nanosat TT&C system now can provide the following functionalities during all mission phases:

- Full-duplex operation in X-band for cat. A and B mission application
- Telecommand uplink
- Telemetry downlink
- Ranging (standard and PN RNG) and range rate operation including Delta-DOR

The Italian equipment started with a development phase in 2021, with a two years activity that brought to a first EM model presented at ISSC on 2023. From the time being a full debugging of the equipment has been carried on with success, and the final configuration of the Cubesat is currently on test bench to complete the test acceptance campaign.
This presentation aimed at provide evidence of the most significant results of the debugging campaign with good perspective of the equipment capability.

B.6 Preventing Mission-Ending Failure: Lessons from and Changes to the Iris Radio

Tom Russell, Dana Sorensen, Tim Neilsen
(Space Dynamics Laboratory)

The Iris Radio has flown on more than a dozen missions without a failure of the radio. However, there have been a small number of temporary anomalies due to avoidable circumstances. This presentation will explore the nature of those anomalies, their on-orbit resolution, and any associated lessons learned. Most spacecraft anomalies involve several points of failure. The flight telecom system is often part of the chain and key to recovering nominal operations.

The presentation will explain approaches the authors have used to avoid these failures. Both hardware and software accommodations have been made to the Iris Radio specifically to prevent mission-ending errors for missions flying Iris. These approaches are distilled into general principles applicable to other missions as well.

C.1 DSN's Emergency Control Complex

Sirina Nabhan, James Buckley
(Jet Propulsion Laboratory, California Institute of Technology)

The Eaton wildfires in Pasadena led to the unprecedented operational activation of the Deep Space Network’s (DSN) Emergency Control Complex (ECC) for the first time in its history. Designed as a backup operations center for the Space Flight Operations Facility (SFOF) at JPL in Pasadena, the ECC ensures continuity of real-time data support for subscribed missions in the event that the SFOF or "dark room" becomes inoperable. On January 7, 2025, this contingency was realized, testing the ECC's capabilities under actual emergency conditions.

This presentation will provide an in-depth overview of the ECC’s role, capabilities, and requirements in supporting mission continuity. It will also examine the cost-benefit considerations for missions deciding whether to invest in this critical service. Furthermore, the presentation will explore the annual ECC training exercises conducted at the Goldstone Complex in Barstow, California. Finally, a detailed analysis of the sequence of events following the disaster will highlight the rapid response measures taken by the DSN to maintain uninterrupted service for its customers. While the ECC is routinely activated for training, this marked its first operational deployment in the DSN’s 60-year history, emphasizing the importance of upgrading services and integrating lessons learned to enhance future resilience.

C.2 NASA Affiliated Deep Space Station 17: IM-2 Mission Support and Beyond

Benjamin Malphrus, Chloe Hart, Emily Walter
(Morehead State University)

NASA and the world-wide space community have a renewed interest in lunar exploration. NASA's Artemis, Gateway and Commercial Lunar Payload Services (CLPS) programs are underway Lunar orbiter and lander missions are being flown by Japan, China, India and others. Commercial ventures (Intuitive Machines, Firefly, iSpace and others) are sending assets to lunar orbit and to the lunar surface. All of these activities require ground support for communications, navigation and tracking- support that requires significant infrastructure including ground stations with large apertures, full-motion antennas and specialized deep space ranging and telecommunication instrumentation. As these services require high data rates, high performance ground stations are needed to close the communications links at great distances. The NASA Deep Space Network (DSN) is generally considered to be heavily subscribed, and, even with the expansion of the new antennas planned, and with the implementation of new techniques (i.e. multiple spacecraft per aperture), the network will be challenged to accommodate the large number of missions expected as the lunar and SmallSat revolutions unfold. The concept of the NASA Lunar Exploration Ground Station (LEGS) network has evolved to provide TT&C and navigation services for these upcoming lunar missions. here is currently a limited number of large-aperture Ka-band stations available globally, making fulfilling the LEGS requirement challenging.

To begin to address this challenge, partnership between JPL and Morehead State University was initiated in 2014 to enhance DSN capabilities by utilizing existing non-NASA assets. The partnership led to an upgrade of the 21 meter antenna to become DSN compatible, resulting in the station becoming an affiliated node on the DSN at X-band, DSS-17. MSU's next goal is to upgrade the 21 meter antenna at toward LEGS compliance. The plan is to implement a full-duplex tri-band (S, X and Ka) system with the receive sensitivity and transmit power sufficient to meet or exceed LEGS requirements. Becoming LEGS compliant is a systems effort, relating to every aspect of a ground station, from tracking specifications, timing references, RF performance, to signal processing methods. In this paper, a high-level overview of proposed upgrades for DSS-17 is provided, beginning with performance metrics required to make the antenna system NASA LEGS compliant and to upgrade the reliability to support lunar missions and to provide NSNS services, while supporting the existing mission set. DSS-17's recent support of the IM-2 lunar lander mission will also be presented.

C.3 Accounting for Orbital Long-Duration Eclipses for Lunar Trailblazer Mission Operations

Miina Anvelt, Bethany Ehlmann, Lee Bennett, Judy Adler, Elise Furlan, Elena Scire

(California Institute of Technology IPAC)

The Lunar Trailblazer mission is a joint mission of Caltech, Jet Propulsion Laboratory (JPL), University of Oxford, and Lockheed Martin Space (LMS) that aims to investigate the presence of water on the Moon and the thermophysical properties of the lunar surface. Based on its reference trajectory, the Lunar Trailblazer (LTB) spacecraft will experience three total lunar eclipses after its late February launch date: March 14, 2025, September 7, 2025, and March 3, 2026 [1]. As a lunar orbiting spacecraft, every instance of a total lunar eclipse causes an extended period when there is a lack of direct solar radiation reaching the spacecraft. During these lunar eclipses, referred to as long-duration eclipses, the spacecraft spends three or more hours in the shadow of the Moon and Earth. This puts the spacecraft systems at risk due to the solar panels being unable to recharge the spacecraft batteries. To optimize power usage, past strategies implemented by lunar orbiting spacecraft have included changing orbital angles, pre-heating heat-sensitive subsystems, and minimizing the battery usage by non-critical subsystems during the eclipse [2]. The minimization of battery usage and pre-heating of subsystems are methods that similarly will be implemented for LTB when entering a long-duration eclipse. The purpose of this study is to outline the mission operations procedure, as an autonomous software sequence, which prepares the LTB spacecraft to ensure power management through long-duration eclipse scenarios. The autonomous sequence was validated on both a virtual machine with a spacecraft software simulator, and a hardware testbed, referred to as the FlatSat, consisting of many of the same components as the spacecraft. The results demonstrated the flexibility of the procedure to timing of the different total lunar eclipses and how the spacecraft can return to nominal operations after a long-duration eclipse scenario.

[1]NASA - Lunar Eclipses (n.d.). Eclipse.gsfc.nasa.gov. https://eclipse.gsfc.nasa.gov/LEdecade/LEdecade2021.html

[2] Mesarch, M. A. (2023, August 13). Long-Term Orbit Operations for the Lunar Reconnaissance Orbiter. Ntrs.nasa.gov. https://ntrs.nasa.gov/citations/20230010952

C.4 A First-in-Flight Demonstration of the Deep Space Network's Multiple Uplinks Per Antenna Capability

Douglas S. Abraham*, Brandon J. Burgett*, Matthew D. Chase*, Jesse C. Fusco**, Dennis M. Heher**, Ethel Grace C. Monte De Ramos***, Shantanu Malhotra*, David D. Morabito*, Robert H. Nakamura**, Matthew C. Napoli**, James A. O'Dea*, Steven M. Olson***, Emily R. Pascua*, Marc Sanchez-Net*, Mazen M. Shihabi*, Dong K. Shin*, Dana Sorensen****, Zaid J. Towfic*

*(*Jet Propulsion Laboratory, California Institute of Technology, **NASA Ames Research Center, ***NASA Deep Space Network, ****Space Dynamics Laboratory, Utah State University)*

In order to mitigate the effects of ever increasing demand for NASA's Deep Space Network (DSN) support, NASA has been developing antenna sharing techniques. These techniques include (Opportunistic) Multiple Spacecraft Per Aperture (MSPA) on the downlink, and the newly developed Multiple Uplinks Per Antenna (MUPA) technique on the uplink. These techniques rely on the fact that multiple spacecraft are in the same beam of a single DSN antenna. In the case of MUPA, the DSN's MUPA system multiplexes Forward Communications Link Transmission Units (FCLTUs) to all the spacecraft that are within the antenna beam onto a single frequency. Each spacecraft identifies its intended transfer frames based on its uplink Spacecraft ID (SCID). This paper discusses the first in-flight test of MUPA features as conducted with the Biosentinel spacecraft, operated by NASA Ames Research Center, carrying the JPL Iris transponder. The successful test of these MUPA features demonstrates the path to enable NASA and the DSN to cope with increased small-sat deployments and the emergence of multi-element lunar exploration missions.

The Biosentinel spacecraft launched onboard Artemis-1 on Nov. 16, 2022 to study the impact of deep space radiation on DNA repair over a long time span spent beyond low Earth orbit. The spacecraft is a 6U CubeSat that hosts the JPL Iris software-defined-radio transponder. The Biosentinel Iris transponder supports features added specifically to aid in MUPA objectives, including: (1) SCID filtering, (2) the ability to change the turn-around-ratio, and (3) the ability for the Iris transponder to perform an onboard sweep to lock on to an uplink carrier that is not Doppler-compensated for the particular spacecraft. At the time of the demonstration, the spacecraft was approximately 0.3AU away from Earth. The demonstration aimed to demonstrate each of the above three Iris MUPA features as well as the heart of MUPA: the DSN-side FCLTU multiplexing capability implemented as the FMUX subsystem at the DSN station.

Two passes were scheduled to support the demonstration, and both passes were fully utilized. The end result yielded a successful result for all success criteria, including the Iris transponder's ability to perform CLTU filtering based on the SCID and dynamic modification of the turn-around ratio. A partial success of the Iris' ability to perform carrier sweep was achieved, complicated by a configuration issue on the DSN transmit side. All of these aspects of the Iris transponder capability shall be discussed in detail in the paper. Finally, complete success was achieved on the DSN CLTU multiplexing capability through FMUX, with two separate clients transmitted CLTUs through FMUX to the spacecraft (with two different SCIDs). The CLTUs were received by the spacecraft and either were ignored (as intended due to having a different SCID than expected by the transponder) or executed (as intended due to a SCID match at the transponder).

This effort and the underlying system engineering are paving the way for the next critical step in implementing MUPA: preparations for a multiplexer demonstration with the SunRISE and EscaPADE projects, which are already in progress.

C.5 Deep Space Network Small Sat Data Management Automated Planning, Logistics, and Learned Operations (APOLLO) Software for Lunar Base Operations

Sivaperuman Muniyasamy, Jekan Thangavelautham
(University of Arizona)

NASA aims to return astronauts to the moon with the Artemis program and establish a lunar base. Over two decades of the International Space Station (ISS) operation, we learned that offloading dull, dirty, and dangerous tasks are crucial in future human exploration as the astronauts spend two-thirds of their time on ISS maintenance tasks. Using robotics only increases in importance in deep space, such as the planned Lunar Gateway, due to the lack of regular astronaut visits and increased cost and complexity in managing base logistics. To address these challenges, Automated Planning, Logistics and Learned Operations (APOLLO) software is being developed to provide physical models, plans, and forecasts with multiple divergent strategies to keep an off-world operational. The software model consists of distributed computing networks that provide situational awareness and forecast events to assist robotics in handling operations. The software is adaptable for the Lunar Gateway/Lunar/Mars base by appropriately varying the parameters for the physical models. The software optimizes various algorithms, such as rule-based Finite State Machines, bio-inspired Evolutionary algorithms, and policy-based Reinforcement Learning algorithms for robotic controllers based on the events and resources available. In this work, we implemented the Finite State Machine (FSM) and Neuroevolutionary controllers for lunar base operations such as logistics handling and firefighting scenarios and compared their effectiveness in throughput time, task completion time, and robustness in failure scenarios. Neuroevolutionary controllers evolved through the iterative optimization of neural networks. Selecting an optimized algorithm for handling operations ensures resilience in operations and system efficiency. This approach enhances autonomy for lunar base operations and can be extended to the Lunar Gateway/ Mars base, enabling safer and more efficient human-robot collaboration. Building on these results, our next phase will integrate reinforcement learning and Neural Cellular Automata to further enhance adaptability under radiation and hardware degradation conditions. Learning from the software will be tested in laboratory conditions to evaluate the algorithms' effectiveness in real-time.

D.1 Kirigami/Origami Actuators for Solar Sail Attitude Control

Hanseong Jo, Christopher Le, Caden Chan, Michael Sicner
(UCLA)

Solar sails are of great interest as the next-generation propulsion, offering propellant-free operation and supporting high delta-V missions and non-Keplerian orbits. Nonetheless, the lightweight and very large-area characteristics of solar sails pose significant challenges for attitude control, which will likely intensify further. Here, leveraging the solar sail's large-area membrane structure, we propose integrating thin-film origami and kirigami actuators within the solar sail membrane to manipulate local radiation pressure for enhanced attitude control. Specifically, we investigate the electrothermal actuation mechanism and develop a new class of bidirectional, ambient-heat-resistant, and fast-cycle actuators suited for solar sail applications. Moreover, by combining kirigami and origami techniques, we morph sheets into complex, multi-degree-of-freedom geometries that facilitate enhanced radiation pressure control. This technology demonstrates the potential to significantly improve solar sailing capabilities, unlock novel missions, and integrate into a broader range of deployable, membrane-based space structures.

D.2 Impulse Space: Pioneering Low-Cost Paths to GEO and Deep Space

Paige Shaw
(Impulse Space)

Impulse Space is building rapid in-space transportation to dramatically lower the cost of reaching high-energy orbits. Helios is a 15,000lbf kick-stage, designed by Tom Mueller, the former CTO of Propulsion at SpaceX for nearly 20 years. Helios can deliver payloads to trajectories with higher C3 values, opening up significantly more transfer opportunities, some with reduced cruise duration. This allows for increased flexibility and lower costs to send more payload mass to the desired orbits, making destinations like Uranus and Mars more accessible for smallsats.

Beyond interplanetary exploration, Impulse Space is transforming access to geostationary orbit (GEO) through its GEO rideshare program, launching for the first time in July of 2026. By consolidating multiple smallsat payloads onto a single launch vehicle, Impulse's rideshare program slashes per-mission costs to levels not previously possible. With a regularly planned launch cadence of dedicated rideshare missions, Helios will take 4+ tons directly from LEO to GEO in less than 24 hours, executing a 2-burn mission trajectory for direct insertion into a GEO graveyard orbit.

The cost reductions delivered by both Helios and the GEO rideshare program are game changers for smallsat interplanetary missions, enabling more frequent and affordable smallsat missions to explore our solar system.

D.3 The Solar Sail Racing Championship: Advancing Interplanetary Propulsion Through Competition

Jessica McGrath, Will Whalen, Jonathan Messer
(Solar Racing Federation)

The Solar Sail Racing Championship (SRC) is an international competition designed to accelerate the development of solar sailing propulsion by challenging teams to race small sail-powered spacecraft from Geosynchronous Orbit to Mars. By leveraging competition as a catalyst for innovation, SRC provides a unique testbed for low-thrust trajectory optimization, sail material advancements, and deep-space autonomy.

The objective is simple: reach and capture into Mars orbit in the shortest possible time. Up to eight CubeSat-class spacecraft, constrained only by pre-deployment mass, volume, and the requirement to rely solely on solar radiation pressure for propulsion, will compete in this high-stakes interplanetary challenge. Teams must design and operate fully autonomous spacecraft, optimizing sail orientation and momentum transfer to navigate a heliocentric trajectory—maximizing acceleration toward Mars and ensuring precise deceleration for orbital insertion.

Beyond the race, SRC serves as a structured platform for advancing solar sailing technology, an underdeveloped yet promising method of interplanetary propulsion. By enabling real-world flight testing, SRC fosters hands-on experimentation, algorithm refinement, and iterative hardware improvements. Future editions will introduce an Unrestricted Class, allowing exploration of emerging concepts such as beamed energy propulsion and coordinated sail formations, potentially revolutionizing deep-space logistics.

This presentation will outline the technical framework, anticipated innovations, and trajectory optimization challenges of SRC, emphasizing its role in shaping the future of low-thrust interplanetary propulsion and small satellite mission design.

D.4 Micro-Mirror Arrays for Solar Sail Attitude Control

Mozakkar Hossain, Tom Joly-Jehenne, Pavel Shafirin, Hanseong Jo, Artur Davoyan
(Department of Mechanical and Aerospace Engineering, UCLA)

Solar sails offer a unique opportunity for future small satellite missions. Future solar sails would necessitate an efficient mechanism for attitude control. Traditional approaches, such as reaction wheels or thrusters, do not scale well to large area sails. Attitude controls based on radiation pressure offer a promising alternative that could be efficiently scaled to very large area sails.

Here, we demonstrate an active high-contrast modulation of radiation pressure. Our approach consists of an array of MEMS micro-mirror switches. When mirrors are in a closed position (OFF-state), the highly reflective Al surface is exposed. In this case, radiation pressure transfers momentum to a sail. Whereas in an open position (ON-state), a transparent underlying substrate is exposed, and no radiation pressure is exerted. We test the performance of fabricated devices by performing spectral reflectance measurements across visible and near-IR bands. Spectral analysis shows that in an ON state, the average reflection (Ron) is ~0.70 in a broad 400 to 700 nm visible window. In an OFF state, the reflection (Roff) is ~ 0.15, as a result, high contrast is achieved. Our tests further show that such MEMS micro-mirror arrays can be operated at >1kHz rate. Our approach allows for a broadband and high contrast switching of radiation pressure with our MEMS micro-mirrors.

D.5 Responsive Access to Cislunar Space Enabled by Rideshare-Compatible Orbit Transfer Vehicles

Mike Loucks*, Stephen West*, Kirby Carlisle**, Ryan Carlisle**
*(*Space Exploration Engineering LLC, ** Argo Space Corporation)*

Conventional architectures for missions operating in lunar orbit or cislunar space have required either a dedicated launch or bespoke accommodation on a high-energy rideshare (e.g. geosynchronous transfer orbit with constrained line of apsides). Small spacecraft bound for cislunar space must wait for a compatible rideshare and accommodate sufficient propulsive capability to transfer from injection to the mission orbit. Orbit transfer vehicles (OTVs) can reduce satellite propulsion requirements by performing most or all of the transfer trajectory maneuvers. If designed to be compatible with commercial rideshare offerings, OTVs can further take advantage of low-cost, responsive access to low Earth orbit (LEO).

After launch with a commercial rideshare to LEO, the OTV performs a series of maneuvers to raise apogee and phase to the appropriate lunar alignment. From this point, the OTV can perform a direct capture into lunar orbit or leverage one or more lunar gravity assists to reach a range of cislunar orbits (e.g. libration point orbit, highly eccentric lunar resonant orbit). To maximize compatibility with commercial rideshare missions (e.g. SpaceX Transporter or Bandwagon), cislunar transfer trajectories for OTVs must accommodate a wide range of initial orbit inclinations.

This presentation presents transfer trajectory designs for rideshare-compatible OTVs from LEO parking orbit to multiple cislunar destination orbits. To illustrate the performance of current and near-term systems, we use Argo Space Corp's "Argonaut" vehicle and its unique water-based propulsion system to demonstrate representative payload masses to a variety of cislunar orbits along with key characteristics of transfer trajectories. Additionally, we will discuss opportunities to deliver payloads from high-inclination LEO (e.g. rideshare to sun-synchronous orbit) to geostationary orbit using one or more lunar gravity assists.

This presentation will highlight the emerging capability of OTVs to deliver cislunar payloads using extant low-cost access to space. This capability represents an opportunity to access cislunar space at reduced cost and on a more responsive timeline than conventional dedicated and high-energy rideshare architectures.

E.1 Mars InfraRed Compact Atmospheric Temperature Sounder (MIRCATS)

Thomas S. Pagano, Michael Mischna
(Jet Propulsion Laboratory, California Institute of Technology)

The Mars InfraRed Compact Atmospheric Temperature Sounder (MIRCATS) is a hyperspectral infrared grating spectrometer that measures radiances in the mid-wave infrared (MWIR) region of the spectrum (4.08-5.13 μm) with nominal spectral resolution of <5 nm in 640 channels. The spectral radiance of carbon dioxide and carbon monoxide features in this band can be used to retrieve profiles of temperature and provide total column CO in the atmosphere. Retrieval simulations have shown that this spectral range and resolution can produce temperature profiles from the surface to about 40 km in altitude with a vertical resolution of 5 km and temperature accuracy of 3 K in clear, daytime low-to-mid latitude scenes. MIRCATS also provides useful information in the presence of dust, in polar regions, and under nighttime conditions. Good sensitivity to the temperature profile in the PBL (surface to 10 km) in a nadir-viewing geometry is a necessary feature of MIRCATS that will allow scientists to measure vertical fluxes of mass, heat and momentum in the martian atmosphere to help address three key science questions about the martian atmosphere: 1) What is the thermal and dust profile of the lower Mars atmosphere? 2) What is the diurnal variability in dust lifting from the martian surface? 3) What is the response of the martian atmosphere to thermophysical forcing by the surface at the 10-100 km scale?

The new and enabling feature of MIRCATS is its global contiguous coverage with over 678,000 soundings each day. This feature improves statistical significance and horizontal and temporal representativeness of the data set beyond current approaches. MIRCATS has a nominal spatial resolution of 13.5 km x 13.5 km and a wide 15.4° x 101° (67 km x 716 km) swath as measured from the spacecraft about nadir from an orbit altitude of 275 km. This scanning geometry can achieve over 80% contiguous coverage of the atmosphere of Mars every day enabling global investigation of small-scale behavior in the atmosphere, which was not previously possible, and allowing us to pursue an entirely new set of science investigations of the martian atmosphere.

A prototype of the MIRCATS is under development at JPL as part of an Earth Science Technology maturation program called the Pyro-atmosphere Infrared Sounder (PIRS). PIRS will fly in an aircraft to measure temperature and water vapor profiles around fires. The same instrument is suitable for flight in a small satellite in Mars orbit.

E.2 SmallSats with Wheels: A Discussion of the V&V Approach for the Cooperative Autonomous Distributed Robotic Exploration (CADRE) Mission

Celeste Smith, Nihal Dhamani, Sawyer Brooks, Adit Sahasrabudhe, Jean-Pierre de la Croix
(Jet Propulsion Laboratory, California Institute of Technology.)

The Cooperative Autonomous Distributed Robotic Exploration (CADRE) mission aims to push the boundaries of multi-agent autonomy on the lunar surface. CADRE, launching in late 2025, will demonstrate key autonomy capabilities on the moon with a team of three rovers. These include collaboratively dividing and exploring a region as well as driving in formation to perform synchronized ground-penetrating radar (GPR) soundings. These soundings will allow us to create a detailed subsurface map of the moon. At the core of this mission is a multi-layered and multi-agent autonomy system, which made CADRE's Verification and Validation (V&V) both crucial and uniquely challenging.

Similar to a traditional SmallSat, CADRE leverages COTS components and an ambitious development timeline. However, unlike traditional SmallSat V&V, surface missions introduce a different set of challenges. Testing in a static lab environment isn't enough—the system must be validated in motion, interacting with real-world terrain, environments, and lighting conditions to fully build confidence in the software and autonomy stacks. With limited hardware, we designed a tiered testing approach—starting with small low-fidelity rovers for early GNC and autonomy validation, scaling up to three development models (DMs) for system-level tests, and relying on flight models (FMs) for critical four-agent operations. V&V had to be fast and adaptive, running in parallel with ongoing development. As both the autonomy software and core FSW evolved, we tested the system in its current state, ensuring a tight feedback loop between developers and testers. Continuous iteration between development, integration, and testing allowed us to quickly identify and address issues, keeping pace with system changes. We focused on end-to-end testing, prioritizing system-wide experiments to catch critical issues early. While we accepted some risk tradeoffs, leveraging CADRE's Type II classification, we ensured that key autonomy demonstrations—such as exploration and formation driving—remained robust and mission-ready.

The V&V campaign for CADRE provided many lessons learned, including the importance of efficient testbeds, hardware availability, and streamlined logistics to support rapid iteration. We also found that strong systems engineering and well-defined autonomy interfaces were crucial, as uncovering issues late in testbed validation was costly and time-consuming. In the end, we successfully demonstrated a full multi-agent autonomy day-in-the-life scenario on FM hardware, proving that CADRE's autonomy could operate reliably under mission-like conditions. This presentation will discuss the approach this project took for V&V and focus on a few main test campaigns which built our confidence in our system.

E.3 Development of a ruggedized rubidium CPT clock platform

Will Krzewick, Igor Kosvin, Matthew Stanczyk, Robert Conners, Chris Higgins, John Bollettiero, Will Emanuel

(Microchip Technology Inc.)

Since their introduction to the commercial market in 2009, microwave atomic clocks using a Coherent Population Trapping (CPT) approach have provided a smaller size, lower power alternate to Rb lamp clocks. By eliminating several complex assemblies, specifically the lamp and microwave resonator, CPT clocks have been able to leverage economies-of-scale and provide a board-mountable, low-cost atomic clock to applications like handheld test equipment and telecom infrastructure.

More recent iterations of CPT clocks have addressed early technical challenges, such as a reliable and rapid lock acquisition time, as well as integration of low noise electronics to improve overall stability metrics such as Allan Deviation (ADEV), phase noise and temperature stability (TempCo). CPT clock performance now approaches the performance of commercially available lamp technology.

Now, CPT clocks have turned towards ruggedization to meet the demanding environmental and performance requirements of aerospace and defense applications.

This paper discusses the challenges and development of a low-profile Rb oscillator platform that leverages CPT cost, size and power reductions into a ruggedized design. This design is intended to offer a wider temperature range compared to commercial variants by employing a novel approach of integrating a thermo-electric-cooler (TEC) into the Rb cell assembly, with a goal of surpassing a range of -40 to +85°C. The design is also intended to accommodate several options including improved short-term stability (ADEV and phase noise) and radiation tolerance. The latter to be addressed in subsequent projects with an approach similar to products such as the space Chip-Scale Atomic Clock (CSAC), which minimally modifies and screens by lot to achieve radiation goals while maintaining a low cost. The improved short-term stability variant is to be addressed by leveraging the latest in low-power evacuated miniature crystal oscillator (EMXO) technology and integrating it into the control loop. The baseline ADEV performance is anticipated to meet 2E-11 @ τ = 1s, while the low noise variant has a goal of 5E-12 @ τ = 1s with a phase noise of -95dBc/Hz @ 1Hz. Experimental results and progress will be shared.

E.4 Quadruped Robots for Extreme Terrain: Bridging Mobility Challenges through Bio-Inspired Innovation

Vigneswari Gowri, Jekan Thangavelautham
(University of Arizona)

Quadruped robots are revolutionizing exploration in extreme environments where conventional mobile robots with tracked and wheeled mobility face significant challenges. Advances in legged mobility have become possible thanks to advances in motors and actuators, electronics, IMUs, and short-range navigation sensors. These legged robots could open the pathway to explore off-world caverns, cliffs, crater walls, and skylights. The legged mechanisms provide exceptional movement on uneven, rugged, or rocky terrain by replicating biological adaptation. However, more needs to be done before legged robot platforms become practical. The challenges with these platforms include integrating suitable autonomous navigation and deployment systems. Further, the robots have problems adapting to certain materials and surfaces in sandy terrains, which are highly uneven. In this presentation, we review some of the state-of-the-art advancements and models and simulate legged robots with advanced navigation/sensing capabilities. Utilizing this advancement, we evaluate the net advantages of cave exploration. Finally, we describe the next steps in the hardware evaluation plan and the platform's demonstration.

F.1 ESCAPADE's Journey: Lessons Learned for low-cost Planetary Missions

Robert Lillis*, Shaosui Xu*, Shannon Curry**, Takuya Hara*, David Curtis*, Hellen Taylor*

*(*UC Berkley Space, **University of Colorado)*

ESCAPADE is a twin-spacecraft Mars mission concept that will revolutionize our understanding of how solar wind momentum and energy flows throughout Mars' magnetosphere to drive ion and sputtering escape, two processes which have helped shape Mars' climate evolution over solar system history.

ESCAPADE will measure magnetic field strength and topology, ion plasma distributions as well as suprathermal electron flows and thermal electron and ion densities, from precessing elliptical 150 x ~8500 km orbits. ESCAPADE are small spacecraft (<200 kg dry mass), following ballistic Hohmann transfers to Mars. Our strategically-designed 1-year, 2-part scientific campaign of temporally and spatially-separated continuous multipoint measurements in different regions of Mars' diverse plasma environment, will allow the cause-and-effect of solar wind control of ion and sputtering escape to be unraveled for the first time.

ESCAPADE is a Category 3 Class D Tailored small satellite mission selected under the SIMPLEX program and funded by NASA's Heliophysics division, with a PI-managed cost cap of <$60 million. Designing, developing, and operating two spacecraft at Mars for this budget necessarily entails a combination of high heritage instrumentation, streamlined processes, a higher risk tolerance than is common for many scientific missions, and an innovative approach to rideshare. ESCAPADE is due to launch on the Blue Origin New Glenn in 2025 or 2026. This presentation will focus on lessons learned by NASA and the ESCAPADE team that may be applied to future low-cost deep space missions.

F.2 Opportunistic System Design for Temporary Moon Exploration from Geosynchronous Orbit

Leonard Vance, Harish Vernekar, Hrithik Thukral, Jekan Thangavelautham
(University of Arizona)

Near Earth Asteroids (NEAs) present a recurring combination of hazards and opportunities for scientists and engineers. The ability to access carbonaceous asteroidal material deepens our understanding of the formation of the solar system, but they also present impact hazards for the Earth, occasionally resulting in planetary extinction events. At the same time, lifting material into cis-lunar space is expensive, so any in-situ refining of material in space saves launch costs into what is becoming an increasing valuable orbital region.

While most NEAs live in interplanetary space and approach Earth at high speeds, it is also true that the Catalina Sky Survey has found some which approach slow enough to be temporarily captured as a temporary moon through chaotic three body interactions with the Earth and the Moon. This paper examines these objects, and explores the possibility of opportunistically exploring them through swarm flybys or rendezvous as a secondary payload from Geosynchronous Earth Orbit (GEO). Optimization of mission requirements are completed, providing a statistical understanding of what would be necessary for such a pre-deployed system.

F.3 2029 Caltech Apophis Mission – ARGOTEC's CubeSats

G. Saita*, L. Pattanaro*, M. Gatti*, N. Ventafridda*, L. Vigna*, L. Conterio*, V. Di Tana*, M. Pereira**, P. C. Adell***, R. Amini***, A. Chmielewski***, L. Fesq***, M. Saing***, S. Bhaskaran***, M. Haynes***, R. Miller***, J. Andrade****, A. Daca****, E. Le Bras*****, K. Stoffels*****, B. Correia******, I. Khantouti******

*(*Argotec Srl., **Argotec Inc., ***Jet Propulsion Laboratory, California Institute of Technology, ****California Institute of Technology, *****EmTronix, ******Tekever)*

The Apophis close flyby with Earth in April 13th 2029 presents a once in seven millennia opportunity to study this 340m Asteroid for science and planetary defense purposes. This event offers a unique chance to study a Near-Earth Object (NEO) very close to our planet, advancing our understanding of their composition and behavior. The Caltech Apophis Mission, developed by an international consortium led by Caltech and JPL, aims to characterize Apophis and demonstrate SmallSat-rapid-response capabilities for potentially hazardous asteroids. The mission concept of operations will feature two 12U CubeSats as payloads, provided by ARGOTEC, that will reach the target asteroid on-board a mothership spacecraft. Once the mothership will complete a mapping of the asteroid prior to Earth Closest Approach (ECA), the two 12U CubeSats will be deployed at about 15 days after the ECA and rendezvous with Apophis at 5-8 radii. Then, once in antipodal orbit, the two CubeSats will perform bistatic radar measurements and optical acquisition in the visible range. The radar will be provided by a consortium led by EmTroniX. Flying in close formation with the mothership spacecraft, the CubeSats will gather data, mapping the entire asteroid surface and acquiring bistatic radar data to characterize the asteroid interior. An Inter-Satellite Link (ISL), based on a S-band radio provided by Tekever, will be established between the three-spacecrafts orbiting around Apophis. This communication network will ensure seamless coordination and data exchange during the mission. Additionally, the CubeSats will support a direct link to Earth through an X-Band transponder. Orbital navigation around a small body like an asteroid poses a challenge due to the uncertainty in the body's shape and rotation state. Optical acquisitions through a NavCam system, as well as classical radiometric measurements, will be carried out to perform the navigation around the asteroid. A cold-gas system to perform reaction wheel off-loading and orbital corrections is included in the baseline design. The spacecraft design leverages ARGOTEC's previous deep-space missions: LICIACube and ArgoMoon. At the same time, the avionics of the 12U, 24 kg CubeSats platform, is based on ARGOTEC's radiation-hardened products, while also leveraging the ongoing design of the HENON project. The Caltech Apophis Mission is currently in its phase A, targeting a launch window in April 2028.

By employing cutting-edge technology to address the challenges posed by the Apophis asteroid, the mission will not only deepen our understanding of NEOs but also demonstrate the rapid-response capabilities necessary for future planetary defense threats

F.4 Longevity in Space: The Space Song Foundation

Julia Christensen, Steve Matousek
(Space Song Foundation)

The Space Song Foundation is a non-profit organization dedicated to exploring ideas of longevity and sustainability at the intersection of art, science, and engineering, on Earth and in outer space. During this presentation, members of the Space Song Foundation will report on their activities over the last year, which include workshops with aerospace engineering students at the University of Arizona and the State University of New York at Buffalo, and an exhibition in the Mojave Desert as part of the Getty Institute's “Art & Science Collide” initiative.

The group's primary project is The Tree of Life, a 200-year public art/science project, using the time frame of 200 years to prompt design decisions. The Tree of Life connects Earth and outer space through a song, which is sent via radio waves between an orbiting spacecraft and an unlikely technological component: a set of live trees that have been activated to operate as large, living antenna systems. The trees and spacecraft will sing a song to each other continuously for centuries, and it will be recorded in real time for 200 years. The song is formed by collecting long-term data sets; that data is “sonified” using custom software. The data-sounds represent the light, soil moisture, and temperature readings at the site of the tree; the spacecraft sings a song describing its own long-term operational capacity. The numbers in these data sets are translated into sonic frequencies and communicated between the trees and spacecraft via radio, so that ultimately, the trees and spacecraft sing a duet for 200 years. The song is open-source and accessible to the public; DJ's can re-mix it, and scientists can use it to detect shifts that can be difficult to glean from centuries-long data sets.

The Tree of Life's “orbiting spacecraft” component is a CubeSat designed to operate for a 200-year lifespan. The Space Song Foundation's work is driven the mission of breaking through the short cycles of technological obsolescence to design space and communication technology that can continually operate for centuries. This goal is driven by the instrumental need to design long-lasting technology to fulfill long-term missions into deep space, and amplified by the human need to think long-term about technology, as e-waste litters our planet, and increasingly, outer space.

The Space Song presentation will include sound, image, and research related to the Tree of Life, and its adjacent projects.

F.5 CATS-I: Reconfigurable CubeSat Swarm for (99942) Apophis 2029 Flyby

Harish Vernekar*, Leonard Vance*, Eric Asphaug**, Victor Lopez*, Path Chawdagor*, Jekan Thangavelautham*
*(*Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona, **Lunar Planetary Laboratory, University of Arizona)*

Planetary defense increasingly relies on rapidly detecting and responding to hazardous near-Earth objects (NEOs), such as asteroid Apophis, which will pass extremely close to Earth in 2029. Traditional single-spacecraft missions often cannot achieve both wide coverage and the agility required to adapt in real time during a transient close encounter. This thesis proposes a reconfigurable multi-CubeSat swarm architecture, launched and recovered by a mothership platform, to enable simultaneous multi-perspective observation and swift reconfiguration for sudden mission demands. A genetic algorithm (GA) is used to determine the optimal number of CubeSats and their deployment trajectories, balancing comprehensive coverage and minimal swarm coordination overhead. Instead of relying solely on conventional 3DOF position control, an adaptive formation reconfiguration approach based on quasi-nonsingular Relative Orbit Elements (ROEs) is introduced. This method employs optimized impulsive maneuvers and incorporates additional shape parameters to maintain the precise inter-satellite baselines essential for high-fidelity stereo imaging. By dynamically adjusting orbital elements in real time, the swarm remains robust against the high relative velocities typical of asteroid flybys and ensures comprehensive surface mapping from multiple viewpoints.

Following the observation phase, each CubeSat performs coordinated redocking maneuvers to rendezvous safely with the mothership. This retrieval not only allows for hardware reuse but also establishes a crucial foundation for In-Space Assembly and Manufacturing (ISAM) operations. Future missions can leverage this redocking capability to incorporate modular repairs, refueling, payload swaps, or the integration of additional CubeSats, effectively laying the groundwork for more advanced in-orbit servicing and assembly. Simulation studies of an eight-CubeSat configuration for Apophis’s 2029 approach confirm that the swarm can achieve extensive stereo coverage with minimal fuel consumption, capturing surface changes during the flyby that would be infeasible for a single craft. More broadly, this framework offers a scalable solution for planetary defense and scientific exploration missions, enabling rapid-response reconnaissance of newly discovered threats and multi-faceted studies of diverse small bodies. By capitalizing on the adaptability, redundancy, and reuse benefits of a carrier-and-swarm system, this work outlines a key step toward future ISAM initiatives and the next generation of autonomous, agile, deep-space exploration architectures.

F.6 A Nano-Lander Concept for In-Situ Exploration of Titan's Hydrocarbon Lakes: A Hitch hike with Dragonfly

Hrithik Thukral, Nathaniel van der Leeuw, Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

Saturn's largest moon, Titan, hosts stable hydrocarbon lakes composed primarily of methane and ethane, making it a prime candidate for investigating prebiotic chemistry and extraterrestrial habitability. While NASA's Dragonfly mission will provide unprecedented insights into Titan's surface and atmospheric dynamics, it lacks the capability for direct liquid sampling. This paper presents a nano-lander concept, a compact (~5-10 kg) autonomous probe, designed to hitch a ride with Dragonfly and deploy into one of Titan's lakes, such as Kraken Mare or Ligeia Mare, to perform in-situ analysis of its liquid environment.

The proposed nano-lander features a floating design, equipped with a microfluidic chemical analyzer, a mass spectrometer, an acoustic depth sounder, and infrared spectroscopy, enabling the detection of complex organic molecules and characterizing Titan's Lake properties. The lander will be deployed mid-flight or post-landing by Dragonfly, utilizing a shock-absorbing aeroshell and parachute system for descent. Given Titan's extreme environmental conditions (-179°C, dense atmosphere, and low sunlight), the lander will rely on radioisotope heater units (RHUs) for thermal management and a lithium-based power system for sustained operations. Data transmission will occur via Dragonfly as a relay or directly to an orbiting asset if available.

This study explores the lander's feasibility, power and communication constraints, and deployment strategies while addressing major technical challenges such as low-temperature electronics, long-duration autonomy, and energy-efficient sensor operations. The mission concept provides a scalable approach to Titan exploration, paving the way for future miniaturized deep-space probes and submersible robotic missions. This work aims to demonstrate the viability of small-scale, low-cost payloads for interplanetary exploration, expanding the scientific return of flagship missions like Dragonfly.

G.1 Metasurfaces for sunlight steering: a tool for satellite attitude control and communications

Tom Joly-Jehenne, Artur Davoyan

(Department of Mechanical and Aerospace Engineering, UCLA)

We developed a method to design metasurfaces (nano-scale textured coatings) that can deflect and diffract light as desired, with an efficiency above 70% for wavelengths between 600nm to 1micron. Those structures can be insensitive to light polarization, making it suitable for sunlight operation, or very narrow-band for laser control. Additionally, they can be insensitive to small incidence variations in some directions, or very dependent to it in some other. All those features offer tools to manipulate all sources of light with a lightweight flat device for various applications. For example, complex light reflection allows a complete attitude control by radiation pressure (photonic propulsion), with a direct integrability onto solar sails. It also shows potential for beam steering and shaping, interesting for precise interplanetary optical communication.

G.2 An Updated Parametric Design of a Torsion Pendulum to Demonstrate Attitude Control Using Microoptoelectromechanical System Control of Radiation Pressure

Jonathan Messer, Joshua Pastizzo
(USC Space Engineering Research Center)

Interplanetary small satellites rely on precise attitude control to maintain orientation, execute maneuvers, and ensure optimal payload operation. Traditional methods, such as reaction wheels and control moment gyros, are constrained by finite onboard propellant for momentum desaturation, limiting mission longevity. Solar radiation pressure (SRP), often the dominant external force in deep space, presents a compelling alternative for propellant-free attitude control. By actively modulating SRP, spacecraft can perform fine attitude adjustments without expending consumable resources.

This work builds upon prior research utilizing microoptoelectromechanical systems (MOEMS) to harness SRP for active attitude control. Specifically, we present an updated parametric design of a torsion pendulum experiment demonstrating closed-loop SRP-based control using a Digital Micromirror Device (DMD). DMDs, commercially mature MEMS technology developed for optical projection systems, consist of millions of individually controlled micromirrors capable of dynamically altering reflectivity patterns. By selectively tilting these micromirrors, the experiment generates controlled torques via SRP, emulating a spacecraft's ability to adjust attitude through radiation pressure modulation.

This updated experimental design addresses key challenges encountered in prior work, including electrical power management, thermal stability, and precision measurement of induced torques. The revised setup incorporates an optimized power system to sustain autonomous operation within a vacuum chamber while minimizing perturbations. Thermal considerations are critical, as vacuum conditions eliminate convective cooling; thus, enhancements in heat dissipation from the DMD and associated electronics are implemented. Mechanically, improvements in the torsion pendulum design, including an increased sensitivity to nanonewton-scale forces, enable more precise characterization of SRP-induced torques. Additionally, alternative methods for measuring rotational displacement are investigated to overcome limitations in the optical lever detection system.

By demonstrating closed-loop SRP control in a controlled laboratory setting, this experiment advances the feasibility of integrating MOEMS-driven attitude control into future interplanetary missions by demonstrating closed-loop SRP control in a controlled laboratory setting. The ability to generate controllable torques without fuel consumption offers significant advantages for long-duration missions, particularly in geostationary and deep-space environments where reaction wheel desaturation remains a limitation. This work provides a critical step toward realizing SRP-based attitude control as a viable complement or alternative to conventional methods, ultimately contributing to extended spacecraft lifetimes and enhanced mission capabilities for small satellites exploring interplanetary space.

G.3 Solving Momentum Management in the Martian Atmosphere

Antoine Bichara
(Rocket Lab)

The density of the Martian atmosphere is highly variable which can lead to difficulties in predicting the amount of atmospheric angular momentum build up on an orbit-to-orbit basis. Existing versions of Mars-GRAM can be orders of magnitude off in predicting the density at a given state. Upcoming missions such as the EscaPADE twin science mission to Mars need to design and test for this variability to lower their orbit periapse progressively into the Martian atmosphere without losing the ability to maintain precise attitude control for both communication and science. Missions that plan to aerobrake at Mars face similar challenges with budgeting for propellant needed to dump atmospheric momentum. This paper presents a robust autonomous momentum management design and testing strategy to best utilize the available momentum envelope provided by the spacecraft when faced with uncertain atmospheric variation. Monte Carlo analysis and HITL verification are performed to assess algorithm performance over the maximum expected density uncertainties. Strategies for performing engine maneuvers at peak aerodensity are discussed, as well as the strategies for tuning the algorithm for minimal reaction control system propellant usage. We hope to reduce the risk for upcoming missions operating in the Martian atmosphere and for future designers to be more effectively able to improve and test the behavior of their GNC systems in uncertain conditions.

G.4 CubeSat Interplanetary Exploration

Olivia Belian
(Savannah River National Laboratory)

CubeSats are small satellites most commonly used by universities, however, nowadays places like the National Aeronautics and Space Administration (NASA) are looking to CubeSats for interplanetary missions. Because of their universal structure it makes them economical, and therefor desirable for deep space. To achieve deep space exploration, we must explore the applications of propulsion and astrodynamics on small satellites. Looking into solar sails, chemical, ion, and nuclear propulsion. To that end keeping CubeSats accessible to the public is very important. Finding the most fuel efficient path and exploring all possibilities is in the best interest of CubeSat interplanetary travel.

G.5 Advancing SMART Devices Ecosystem to Accelerate Lunar and Martian Surface Exploration and Development

Jekan Thangavelautham
(Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory, University of Arizona)

Resurgent international interest in lunar surface exploration and development has seen numerous planned and ongoing missions. These efforts have seen commercial interest and missions from a variety of new players, resulting in the transport and deployment of fleets of space hardware, including landers, rovers, and science instruments. Each party has the right of way to perform its lunar surface mission. Yet more can be achieved on behalf of Earth's taxpayers. In this presentation, we briefly explore how ad-hoc cooperation and coordination between surface assets can be used to increase the robustness, effectiveness, and length of missions.

We analyze an ecosystem of surface devices that can enhance this type of cooperation, including the use of mobile control towers, smart sandbags, and distributed computing paradigms. Structures built on a lunar base and their surrounding would consist of modular components that can sense, collect, process, store, and communicate information in a distributed network. These networks can make localized decisions independently and offload routine maintenance responsibilities from astronauts.

We further examine the technologies and algorithms available to establish a distributed network within modular base building block components. We analyze sandbags embedded with electronics as a potential candidate for modular building block components. These sandbags demonstrate multi-functionality with different schemes of embedded electronics. Lastly, we examine how this distributed computational infrastructure can cohesively work to both avert disasters and rebound from them.

Talk Title: Advancing SMART Devices Ecosystem to Accelerate Lunar and Martian Surface Exploration and Development

G.6 SmallSat Orbit Determination Using Onboard One-Way Radiometric Tracking And Atomic Clock

Todd Ely, Margaret Rybak
(Jet Propulsion Laboratory, California Institute of Technology)

The Recent demonstrations of one-way radiometric tracking using the Iris radio paired with a Chip Scale Atomic Clock (CSAC) on NASA's CAPSTONE mission have shown the data to be sufficient for orbit determination (OD) with modest requirements [1]. Since that initial work, data collected over almost a year have been analyzed in developing an improved calibration model. In this presentation, we will present the current state of development for the improved modeling and point to the work remaining. Furthermore, we will characterize the possible improvement in OD that could be obtained with a more stable Miniature Atomic Clock (MAC) on a lunar orbiting satellite.

[1] T. A. Ely et al., "Orbit Determination Demonstration Using Onboard One-Way Radiometrics from the Iris Radio on the Capstone Mission," presented at the AAS/AIAA Astrodynamics Specialist Conference, Broomfield, CO, Aug. 2024.

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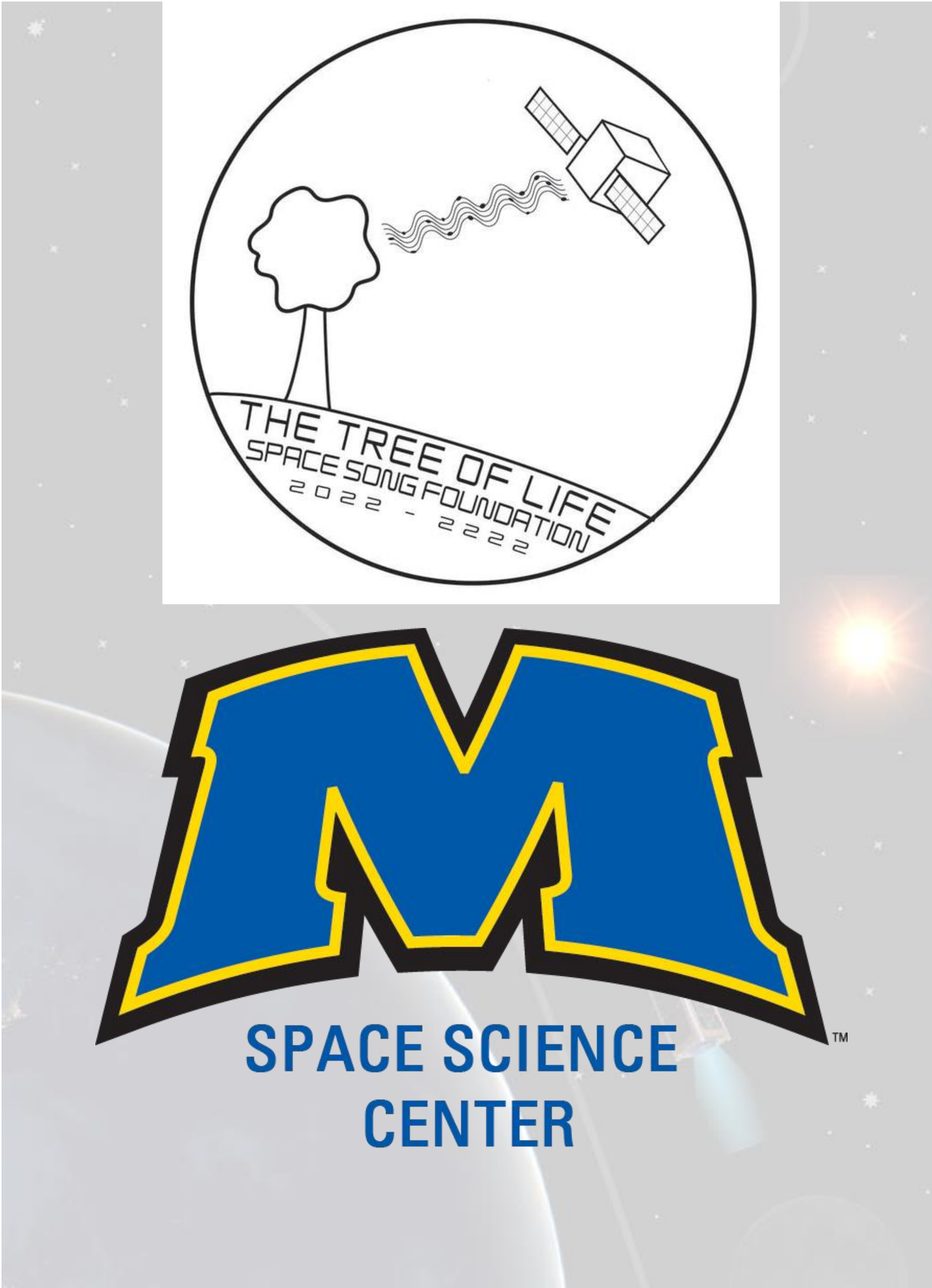
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