



LCPM-12 2017

Low-Cost Planetary Missions Conference

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BOOK OF Abstracts

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SESS01 - AGENCY PROGRAMS AND PLANS FOR LOW-COST PLANETARY MISSIONS

SESS01-02: THE CNES FRENCH SPACE AGENCY PLANETARY PROGRAM – LOW COST PERSPECTIVES

Mr. Pierre Bousquet¹

¹Cnes, Toulouse, France

French involvement in affordable deep space missions has been illustrated recently by the accomplishment of the Philae lander mission, and by the launch of the Mascot lander, developed with DLR, which will be dropped in 2018 by JAXA's Hayabusa 2 probe on the Ryugu asteroid. On both occasions, the complementarity of CNES dedicated engineering skills, such as mission analysis for the descent to small bodies, and of French laboratories know how in the development of high performance – miniaturised instruments, has been demonstrated. CNES' extensive expertise in picture processing, built up through our laboratory on Autonomous Navigation for planetary rovers, has also proved very valuable during the post-processing of the images to reconstitute Philae's trajectory on the basis of the images taken during its descent.

The most salient characteristics of our contributions to Philae and Mascot will be presented during a first part of our talk. We will in particular show how we can build on this experience to optimise the throughput of imagers with extensive real time data compression, processing and selection.

In a second part of our presentation, we will elaborate on the perspectives drawn out in a Mars roadmap recently formulated by the French planetology community. Miniaturisation and cost reduction have been identified as essential assets to enable ground-braking scientific observatories such as:

- Geophysics and meteorological surface networks,
- Orbital networks sensing the influence of the solar wind on the magnetosphere,
- Surface networks for a regional characterisation of radiation fluxes,
- Drones and agile rovers to increase the density of in-situ measurements for surface science and exobiology.

SESS01-03: ISAS/JAXA EXPLORATION PROGRAM INTO SOLAR SYSTEM

Prof. Hitoshi Kuninaka¹

¹ISAS/JAXA, Sagamihara, Japan

Sakigake and Suisei spacecraft explored Halley comet in 1985. ISAS/JAXA has sent many spacecraft into the Solar System since those days. Hayabusa accomplished the round trip between an asteroid and Earth, and then Hayabusa2 is approaching to another asteroid now. Akatsuki is observing Venus. Mercury Magnetosphere Orbiter (MMO) will be launched with BepiColombo next year. Hiten and Kaguya flew around Moon, and SLIM will land on it. Mars Moon eXploration (MMX) is under development. In Pre phase A and Phase A, several deep space missions are warming up now: Destiny+ for comet, Solar Electric Sail for Trojan asteroid, and so on.

SESS02 - LOW-COST MISSION INFRASTRUCTURE AND CONSIDERATIONS

SESS02-01: OPAG VIEWPOINT: ARE SMALL SPACECRAFT OR LOW-COST MISSIONS USEFUL FOR EXPLORATION OF GIANT PLANETS AND OCEAN WORLDS?

Prof. Alfred McEwen¹, Dr. Linda Spilker², Prof. Jason Barnes³, Dr. Pat Beauchamp², Dr. Jeff Bowman⁴, Dr. Scott Edgington², B⁵, Dr. Mark Hofstadler², Dr. Terry Hurford⁶, Dr. Jeffrey Moore⁷, Prof. Carol Paty⁸, Dr. Julie Rathbun⁵, Prof. Kunio Sayanagi⁹, Prof. Britney Schmidt⁸, Dr. Elizabeth Turtle¹⁰

¹University Of Arizona, Tucson, United States, ²Jet Propulsion Lab, Pasadena, United States, ³University of Idaho, Moscow, United States, ⁴Scripps Institute of Oceanography, La Jolla, United States, ⁵Planetary Science Institute, Tucson, United States, ⁶Goddard Space Flight Center, Greenbelt, United States, ⁷Ames Research Center, Mountain View, United States, ⁸Georgia Institute of Technology, Atlanta, United States, ⁹Hampton University, Hampton, United States, ¹⁰JHU Applied Physics Lab, Laurel, United States

Smallsats are very useful in low-Earth orbit because they do not need large propulsion, telecom, or power systems, do not have radiation design challenges, and do not need to demonstrate reliability over a long lifetime. None of this is true for missions that visit the Outer Planets and Ocean Worlds. All past and planned independent spacecraft to Jupiter or beyond are large. Discovery-class missions to the outer solar system may be feasible, but none yet has been selected. Discovery proposals have been submitted to explore Jupiter, Titan, Enceladus, and Io; none has been proposed (to our knowledge) to explore the distant Ice Giants. In addition, a dedicated space telescope to observe solar system planetary bodies may be feasible within a Discovery-class budget, and has been proposed several times. The recent Congressional directive about an Ocean Worlds Program that includes Discovery may prove difficult to accomplish. Small subsatellites or probes that ride along with larger missions are feasible, as demonstrated by the Galileo and Huygens probes, although they have not been low in cost. Subsatellite concepts were considered but rejected for Europa Clipper. However, with piquing congressional interest and funding in STMD for CubeSats together with interest and funding in the NASA Planetary Science Division, the incorporation of SmallSats may enhance future missions. As the technology matures and the reliability improves, the likelihood of missions using SmallSat components should increase. Two new concepts for Outer Planets are under study, funded by the Planetary Science Deep Space SmallSat Studies (PSDS3), to probe atmospheres and characterize magnetospheres.

SESS02-02: THE ROLE OF SMALL SATELLITES IN ADDRESSING MARS SCIENCE GOALS

Dr. Jeffrey Johnson¹, Richard Zurek², David Beaty², Serina Diniega², Scott Hubbard³, Michael Meyer⁴, Phil Christensen⁵, Lisa Pratt⁶, Gian Ori⁷, Don Banfield⁸, Ben Bussey⁴, James Ashley²

¹JHU/APL, Laurel, United States, ²JPL, Pasadena, USA, ³Stanford University, Stanford, USA, ⁴NASA HQ, Washington, USA, ⁵ASU, Tempe, USA, ⁶Indiana University, Bloomington, USA, ⁷IRSPS, PESCARA, ITALY, ⁸Cornell Univ., Ithaca, USA

Small satellite technologies can address several fundamental science questions relevant to the Mars Exploration Program. The high priority Mars science goals identified in both the MEPAG Goals Document <http://mepag.jpl.nasa.gov/reports.cfm> and the last Planetary Science Decadal Survey



included determining: 1) if life ever arose on Mars (Goal I), 2) the processes and history of modern and ancient climates (Goal II); and 3) the evolution of the surface and interior of a changing, Earth-like planet (Goal III). While large strategic missions, such as science-driven sample return, are critical to addressing many key aspects of these goals, there remain avenues for low-cost missions to address other science issues related to modern and ancient episodic climate and environmental changes, atmospheric loss, and sources and cycling of surface, near-surface, and polar volatiles (including water, carbon dioxide and hydrocarbons). For example, the temporal variability, amount, and source of trace gases like methane might be addressed by small satellites to constrain the nature of its source (biological or geochemical) and monitor changes vital to understanding its dynamics in the atmosphere. For some science objectives, small satellites in combination with MEP missions could be a winning strategy. The medium-to-large class MEP missions, especially those with Solar Electric Propulsion, could carry small satellites into orbit, and their orbital infrastructure could relay the small satellite data back to Earth, mitigating two of the major constraints on small satellites operating in Mars vicinity. In turn, the small satellites could focus on key Mars science investigations, especially those benefiting from novel orbits (e.g., those that perform deep dives into the atmosphere) or from multiple small satellites (e.g., spacecraft-to-spacecraft occultations). Low-cost access to the surface is highly desirable, of course, given the high diversity of Mars and the challenges of understanding this complex planet. In addition, small satellites may be suited to demonstrating or becoming resource surveyors or climate monitoring systems that may be needed to aid future robotic or human exploration of the Mars system. Such mission(s) would directly address the MEPAG Goal IV: Preparation for Humans. This presentation will examine how low-cost missions could contribute towards addressing high priority Mars Goals, as viewed by the MEPAG community.

SESS02-03: ARCHIVING LOW-COST MISSION DATA IN NASA'S PLANETARY DATA SYSTEM

Dr. Nancy Chanover¹, C. Acton², R. Walker³, E. Guinness⁴

¹New Mexico State University, Las Cruces, United States, ²Jet Propulsion Laboratory, Pasadena, USA, ³University of California Los Angeles, Los Angeles, USA, ⁴Washington University St. Louis, St. Louis, USA

NASA's Planetary Data System archives electronic data products from NASA planetary missions sponsored by NASA's Science Mission Directorate. It actively manages the archive to maximize its usefulness, and the PDS has become a basic resource for scientists around the world. All PDS-curated products are peer-reviewed, well-documented, and available online to scientists and to the public without charge. The PDS uses standards for describing and storing data that are designed to enable future scientists who are unfamiliar with the original experiments to analyze the data. These standards address the data structure, description contents, media design, and a set of terms. The PDS works closely with project teams to help them design well-engineered products that can be released quickly. While PDS-curated products are freely available online, the PDS provides teams of scientists to help users select and understand the data. The PDS is organized as a federated data system; data are archived by scientist-led organizations, called Discipline Nodes, which present a single interface to the world (<http://pds.nasa.gov>) and which are organized around broad areas—some based on scientific discipline, some by target body type, and some by sensing modality.

In addition to planetary data obtained from a range of mission classes (flagship, New Frontiers, and Discovery), the PDS can also archive data resulting from smaller flight projects such as SmallSats, CubeSats, and suborbital experiments. Furthermore, new requirements put forth for data management from both research and development data analysis programs and peer-reviewed journals have increased the amount of derived data

being submitted for archiving to the PDS. Hence the PDS is adapting to a broader definition of mission data in its archiving goals. In this presentation we discuss the potential role of the PDS in data archiving for low-cost planetary missions, and we review fundamental concepts surrounding the PDS architecture and archiving process.

SESS02-04: SPICE CAN HELP SMALLSAT MISSIONS OBTAIN IMPORTANT, ACCURATE OBSERVATION GEOMETRY

Mr. Charles Acton¹

¹JPL, Pasadena, United States

NASA's SPICE information system provides scientists with the observation geometry needed to plan observations from instruments aboard robotic spacecraft, and to subsequently help in analyzing the data returned from those observations. In this sense "ancillary data" are items such as spacecraft orbit and attitude; target body size, shape and orientation; instrument field-of-view size and orientation; and time system computations. SPICE comprises not only these data, but also a set of software modules (subroutines) collectively known as the SPICE Toolkit, used to read those SPICE data and compute many useful derived quantities such as spacecraft altitude, sub-spacecraft LAT/LON, instrument field-of-view projection on a planetary surface, and lighting angles. SPICE users incorporate a few of these modules into their own application program to accomplish whatever geometry calculations are needed.

The SPICE system has been in use on worldwide planetary missions starting from the Magellan mission to Venus. In recent years the use of SPICE has expanded to include space physics and even earth science missions. With the growing interest in "small" missions, we take the opportunity of this Low-Cost Planetary Missions Conference to introduce SPICE to a new audience, believing that many of these missions have the same needs for observation geometry as the larger missions have had, and believing that SPICE can offer an affordable solution to meeting those needs.

The research described in this publication is carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

SESS02-05: RISK MITIGATION APPROACH FOR SMALLSATS

Dr. Harald Schone¹, Dr. Pat Beauchamp¹, Dr. Doug Sheldon¹, Dr. Michael Johnson²

¹Jpl/Caltech, Pasadena, United States, ²NASA/ GSFC, Greenbelt, USA

Historically, it was understood and accepted that "high risk" and "CubeSat" were largely synonymous and therefore eliminated CubeSats from many mission opportunities. Further, mission risk postures span from "do no harm", to those whose failure would result in loss or delay of important science opportunities. These issues motivated a workshop between a government consortium, industry and academia. The two-day workshop had the objective to foster a collaborative public-private dialogue. The recommendations of the workshop lead to a new risk communication approach that rates the risk based on opportunity cost and provides an approach to share risk with experienced CubeSat manufacturers. A general overview of this approach will be given.



SESS02-06: VENUS BRIDGE: A SMALLSAT PROGRAM THROUGH THE MID-2020S

Robert Grimm¹, James Cutts², Venus Bridge Focus Group³
¹Southwest Research Institute, Boulder, United States, ²Jet Propulsion Laboratory, Pasadena, United States, ³At Large

In order to provide some continuity between Magellan and any potential future medium-to-large United States mission, the Venus Exploration Analysis Group (VEXAG) has been directed by NASA's Science Mission Directorate to determine if useful Venus exploration can be performed within a \$200M cost cap. This naturally suggests multiple smallsats or cubesats. The Venus Bridge Focus Group is considering ideas on architectures, technology, and science that could be pursued within such a framework

Architectures could include stand-alone missions (including launch vehicle), missions deployed from spacecraft that do not encounter Venus, missions that free-fly following injection toward Venus, missions that are released at Venus fly-by, or cooperative use of resources with non-Venus missions. Mission profiles can include fly-bys, orbiters, probes, or landers.

Venus Bridge is an opportunity to study new technology. The Focus Group is considering propulsion, communications, atmospheric-probe, aerial-platform, lander, and other technologies that can be accommodated in a smallsat or cubesat format.

A key aspect of the study is to consider linkage between missions that might not otherwise arise without strategic direction. For example, probe or lander missions may require a telecom relay, e.g., an orbiter already on-station.

The Focus Group received about a dozen concepts from the community and is collating them into basic architectures. A subset of mission implementation studies with cost estimates will be performed this summer. The Focus Group then will be able determine feasible combinations of mission architectures that can be matched to VEXAG science goals, technology, and roadmap documents. A final report will be delivered to NASA early in 2018.

Venus Bridge is a unique opportunity to test new spacecraft technology in linked missions while providing new science ahead of the next generation of medium-to-large Venus missions.

SESS03 - ACTIVE MISSIONS AND MISSIONS CURRENTLY UNDER DEVELOPMENT FOR LAUNCH IN THE NEAR FUTURE

SESS03-01: CURRENT STATUS AND PROXIMITY OPERATION OF MINERVA-II ROVERS ONBOARD HAYABUSA2 ASTEROID EXPLORER

Dr. Tetsuo Yoshimitsu¹, Prof. Takashi Kubota¹, Dr. Atsushi Tomiki¹
¹Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagami-hara, Japan

MINERVA-II is an onboard payload of Hayabusa2 asteroid explorer which was launched in 2013 and is now heading for Asteroid Ryugu to make a rendezvous in 2018.

MINERVA-II is composed of three rovers to make scientific observations on the asteroid surface. They will make autonomous explorations over the microgravity environment

of the asteroid after the deployment from the mother spacecraft at the vicinity of the surface.

All the rovers were developed without the official budget from the mission to seek for low-cost technology-driven challenges on the surface of the target asteroid.

There are two chances to deploy rovers onto the asteroid surface. Two twin rovers developed by the authors are packed into one container and are deployed at the same time. Another one installed in the secondary container are mounted at the opposite side of the mother spacecraft. Two deployment processes are almost the same.

All the rovers as well as another lander developed by DLR and CNES have an identical communication system. Even when all the surface probes are alive at the same time, the relay module onboard the mother spacecraft can get the telemetry data from all the probes simultaneously.

The rovers make an autonomous exploration by hopping. Two types of cameras are installed in the rovers. A pair of stereo cameras can get precise surface features when the rover is on the surface, while the wide angle camera is used to get overall sceneries from the above when the rover is hopping.

There is a range measurement capability equipped with the communication system. The resolution is not so precise, but the rover relative positions may be estimated after the deployment of the rovers.

The hopping capabilities and the deployment behavior of the rovers were finally evaluated by microgravity experiments using a drop tower after the launch.

This paper describes the post-launch evaluation of the rover system as well as the operational issues after Hayabusa2 have arrived at the asteroid.

SESS03-02: ASTEROID IMPACT AND DEFLECTION ASSESSMENT (AIDA): THE DOUBLE ASTEROID REDIRECTION TEST (DART) MISSION

Ms. Cheryl Reed¹, Dr. Andrew Cheng¹, Dr. Andrew Rivkin¹, Dr. Brian Kantsiper¹
¹JHUAPL, Laurel, United States

The Double Asteroid Redirection Test (DART) is a small NASA mission under the auspices of the NASA Planetary Defense Coordination Office. DART completed a NASA Phase A study in 2016, and began Phase B, June 1, 2017. DART will be the first mission to demonstrate an asteroid impact hazard mitigation technique, by using a kinetic impactor to deflect an asteroid.

DART is part of the Asteroid Impact & Deflection Assessment (AIDA) mission, an international cooperation between NASA and ESA. AIDA consists of two independent mission elements: the NASA Double Asteroid Redirection Test (DART) mission [1] and the ESA AIM rendezvous mission [2]. The primary goals of AIDA are to test our ability to perform a spacecraft impact on a potentially hazardous near-Earth asteroid and to measure and characterize the deflection caused by the impact. AIDA, with both DART and AIM, will offer the first fully documented impact deflection experiment at asteroid scale.

The DART target will be the moon of the binary asteroid (65803) Didymos, with the deflection experiment to occur in October 2022 when Didymos will be on a close approach to the Earth. The DART impact on the secondary member of the binary asteroid will alter the binary orbit period, and this change can be measured by Earth-based observatories. The DART impact



on the Didymos moon changes its orbital speed by ~0.6 mm/s, which causes an orbital period change of ~7 minutes (~1% of the orbital period). This change is readily measured not only by Earth-based telescopes but also by the AIM rendezvous spacecraft.

DART's target, the secondary member of [65803] Didymos, is within the likely size range for an asteroid that humankind may try to deflect to avoid a catastrophic impact on Earth. The target body diameter of ~160 m is large enough to be a Potentially Hazardous Asteroid (PHA) in its own right if it were a single asteroid. If an NEO of this size were to impact Earth, it would release an impact energy ~400 MT TNT and would cause regional devastation over more than a metropolitan area. There are over 7,000 known NEOs as of Jan. 2017 at a size of ~140 m or larger.

The DART kinetic impactor baseline mission design has changed from that described in [1]. DART will launch as a secondary payload to geosynchronous orbit and use the NASA Evolutionary Xenon Thruster (NEXT) ion propulsion system to spiral out from Earth orbit and transfer to Didymos. The DART impact on the Didymos moon will occur on Oct. 7, 2022. With NEXT ion propulsion and launch as a commercial rideshare, DART has a robust 5 month launch window which opens December 2020. DART will be the first mission to demonstrate the NEXT ion propulsion system.

We will present and update the program status of DART and AIDA.

SESS03-03: DESTINY+: DEEP SPACE EXPLORATION TECHNOLOGY DEMONSTRATOR AND EXPLORER TO ASTEROID 3200 PHAETHON

Dr. Hiroyuki Toyota¹, Dr. Kazutaka Nishiyama¹, Dr. Yasuhiro Kawakatsu¹, Mr. Shunsuke Sato¹, Dr. Takayuki Yamamoto¹, Mr. Shun Okazaki¹, Mr. Tetsuya Nakamura¹, Prof. Ryu Funase², Dr. Takaya Inamori³, Dr. Tomoko Arai⁴, Dr. Ko Ishibashi⁴, Dr. Masanori Kobayashi⁴
¹Jaxa, Sagami-hara, Japan, ²The University of Tokyo, Bunkyo-ku, Japan, ³Nagoya University, Nagoya, Japan, ⁴Chiba Institute of Technology, Narashino, Japan

DESTINY+, which stands for "Demonstration and Experiment of Space Technology for INterplanetary voYage, Phaethon fLyby with reUSable probe," is a mission candidate for JAXA's next small scientific program, which utilizes a newly developed low-cost solid rocket, Epsilon. DESTINY+ is a demonstrator of a next-generation high performance deep space transportation system with the maximum delta-v capacity of 5 km/s. It can deliver a payload of 50 kg from a highly elliptical orbit around the earth to trajectories to flyby Mars or Venus by a spacecraft with the total mass of 500 kg. If the spacecraft is injected directly into an interplanetary orbit, it can deliver a payload of 200 kg to orbits around Mars or Venus. The key technologies of this platform are ion engines, ultra lightweight solar panels, advanced thermal control devices, novel orbit design and lightweight compact avionics. DESTINY+ will also demonstrate multiple flyby explorations of near earth objects (NEOs). The first target is one of the most unusual comet-asteroid transition bodies, 3200 Phaethon, which is famous as a parent body of the Geminids meteor shower. Because of its small perihelion distance of 0.14 AU, dehydration of the surface material by solar heating is expected, but some primitive hydrous material may still reside in its interior. Phaethon is an ideal body to understand on-going thermal evolution of primitive bodies in the solar system. Furthermore, Phaethon is among the largest potentially hazardous asteroids (PHAs), which cross the Earth's orbit. Thus, Phaethon is a critical mission target in the context of science and planetary defense at the same time. Due to Phaethon's elliptical orbit with a high inclination of 22.2 degrees, DESTINY+ is required to perform a 25 km/s velocity flyby Phaethon at a distance of 500 km for

observation. The spacecraft will carry a telescopic panchromatic camera to observe geological features and a multi-band wide-angle camera to observe the diversity of the surface. Just before the flyby, DESTINY+ will release a 6U CubeSat, PROCYON mini, which will flyby Phaethon at a distance of 50 km by optical navigation. PROCYON mini will be docked to the mothership again after the flyby, and will be released again before the next flyby. DESTINY+ will also carry a dust analyzer, which will be supplied by DLR, to observe interstellar and interplanetary dusts as well as dusts originating from Phaethon. We aiming to launch DESTINY+ in 2022, and encounter Phaethon in 2026.

SESS03-04: ASTEROID RESOURCE EXPLORATION MISSION BY RECONNAISSANCE AND LANDED INVESTIGATION

Dr. Yonghe Zhang^{1,2}, Dr. Yamin Wang^{1,2}, Dr. Yang Gao³, Dr. Jun Huang⁴, Dr. Qingwen Wu⁵, Chengbo Qiu^{1,2}, Yukun Sun^{1,2}, Xiaoyong Guo⁶, Zhencai Zhu^{1,2}, Yingjie Yu^{1,2}
¹Key Lab of Microsatellite, Chinese Academy of Sciences, Shanghai, China, ²Shanghai Engineering Center For Microsatellites, Shanghai, China, ³Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences, Beijing, China, ⁴China University of Geosciences, Wuhan, China, ⁵Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, China, ⁶Key labs management office, Bureau of Major R&D Programs, Chinese Academy of Sciences, Beijing, China

Shanghai Engineering Center for Microsatellites (SECM), which has been developed near twenty satellites into Earth orbit for space science, communication and navigation, and Earth observation, now shows an increasing interest of exploring deep space targets in a cost-effective way. Asteroid Resource Exploration Mission by Reconnaissance and Landed Investigation (AREM) is the first interplanetary mission of SECM, and has been planning and researching for one year. By sending a small spacecraft to a near Earth asteroid to survey the resources composition, internal structure, and fine mapping, the category of mineral and mining environment can be better understood. This could lead to future asteroid mining as well as resource utilization mission.

In order to reduce the mission budget, AREM is considered as a secondary payload on the Long March 3 Rocket riding up to Geostationary Transfer Orbit and takes full advantages of Moon and Earth gravity assists to obtain the desired heliocentric trajectory with minimal cost. Several 100 m diameter asteroids, 2013WA44, 2007YF, 2012UUV136, 2005TG50, 2001CQ36, have been selected as the candidates on the constraint of 2020-2022 launch windows.

AREM's 1.5-year primary science phase begins with approaching its 100 m diameter target asteroid from 100000 km faraway using imaging to determine shape and pole position. Then, slowly km-distance flyby trajectories are designed to estimate the mass and rough gravitational field. Global topography and mapping are completed by progressively lower flyby trajectories with different solar elevation. After obtaining fine global map and gravitational field, spacecraft descends to a low orbit for very high-resolution characterization of the surface, and to select the land site. In the meantime, multispectral imaging is used for mineralogical, water, and organics measurements.

Finally, it deploys a small hopping rover to the surface of target asteroid. Due to the microgravity and vacuum characteristics of asteroid, the way of hopping becomes a viable way of detecting. The hopping robot mainly consists of flywheel shafting, external frame, brake mechanism, and scientific payloads. It weighs about 4.5 kg. With the quickly braking by the



braking mechanism, the torque of the flywheel is transmitted to hopping. So it can move in the three-dimensional direction on the asteroid, including swing, roll and hop. Laser gyro and high precision range sensor input the attitude and position to ensure the accuracy of the hop path by feedback control. By high-resolution surface images and temperature gradient obtained by the scientific payload system, the alternative land sites could be identified.

SESS03-05: NEAR EARTH ASTEROID (NEA) SCOUT CUBESAT MISSION

Anne Maritan¹, Julie Castillo-Rogez¹, Les Johnson², Jared Dervan², Calina Seybold¹, Erin Betts²

¹Jet Propulsion Laboratory, California Institute Of Technology, Pasadena, United States, ²NASA George C. Marshall Space Flight Center, Huntsville, United States

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

Acknowledgements: The authors would like to thank the members of the Near Earth Asteroid Scout project and engineering team at NASA MSFC, NASA's Langley Research Center and the Jet Propulsion Laboratory who are making it happen. We would also like to thank the NASA Human Exploration and Operations Mission Directorate for funding the project and the dedicated team developing the Space Launch System that is going to be our ride into space.

SESS03-06: THE LUNAR POLAR HYDROGEN MAPPER CUBESAT MISSION

Dr. Craig Hardgrove¹, Dr. James Bell¹, Igor Lazbin², Joe DuBois¹, Stephen West¹, Hannah Kerner¹, Dr. Erik Johnson³, Dr. Mike Tsay⁴, Dr. Alessandra Babuscia⁵, Eric McNaul⁶, Steve Stem⁷, Derek Nelson¹⁰, Anthony Genova⁸, David Dunham¹⁰, Bobby Williams¹⁰, Robert Amzler¹, Nathaniel Struebel¹, Dr. Paul Scowen¹, Dr. Tony Colaprete⁸, Dr. Richard Starr⁹, Dr. James Christian⁹
¹Arizona State University, Tempe, United States, ²AZ Space Technologies, LLC, Tempe, ³Radiation Monitoring Devices, Watertown, ⁴Busek, Natick, ⁵Jet Propulsion Laboratory, Pasadena, ⁶MMA Designs LLC, Boulder, ⁷Blue Canyon Technologies, Boulder, ⁸NASA Ames, Moffett Field, ⁹Catholic University of America, Washington, ¹⁰KinetX Aerospace, Tempe

The Lunar Polar Hydrogen Mapper (LunaHMap) is a 6U CubeSat mission recently selected by NASA's Science Mission Directorate to fly as a secondary payload on first Exploration Mission (EM-1) of the Space Launch System (SLS). LunaH-Map is led by a small team of researchers and students at Arizona State University, in collaboration with NASA centers,

JPL, and commercial space businesses. The LunaH-Map mission will help constrain hydrogen abundances at spatial scales below 10 km in order to understand the relationship between hydrogen and permanently shadowed regions, particularly craters, at the Moon's South Pole. The mission's primary payload is a miniature neutron spectrometer (Mini-NS) designed to measure count rates of epithermal neutrons. Enabled by a low-thrust ion propulsion system, LunaH-Map will achieve lunar orbit insertion within ~12 months of SLS separation and maneuver into a highly elliptical, low perilune orbit centered around the South Pole of the Moon. In this orbit, LunaH-Map will achieve over 140 low-altitude flybys of the South Pole during its two month science phase. LunaH-Map and two fellow secondary payloads selected by NASA to fly on SLS EM-1 will be the first CubeSats to explore the Moon and interplanetary space.

SESS03-07: EXPERIMENTAL RESULTS OF FORMATION CONDITIONS AND COMPOSITION OF COMETS AS DERIVED FROM ROSETTA'S MEASUREMENTS

Dr Diana Laufer¹, Prof. Akiva Bar-Nun¹, Adi Greenberg-Ninio¹

¹Tel Aviv University, Tel Aviv, Israel

Experimental results of formation conditions and composition of comets as derived from Rosetta's measurements
Diana Laufer(1), Akiva Bar-Nun(2), Adi Ninio-Greenberg
Dept. of Geophysics, Tel-Aviv University, Tel-Aviv, Israel, 6997801
Email: dianal@post.tau.ac.il

Rosetta spacecraft at the comet 67P/Churyumov-Gerasimenko delivered most important scientific data on comets.

Laboratory studies are essential to evaluate comets' formation conditions and their evolution and also to interpret the received data from Rosetta. Direct measurements together with laboratory experiments help improve our understanding the nucleus interior structure and composition, the surface covered with cracks and craters and also the volatiles in the coma formed along the orbit around the Sun.

The findings of our laboratory experiments can set the formation temperature by the trapping mechanism of gases in amorphous ice as compared to new direct measurements by the Rosetta spacecraft on Comet 67P/C-G. The measured noble gases Ar, Kr and Xe, without Ne, together with the N measurements set the grains formation temperature at ~30 K. One of the most surprising measurements of the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis instrument, ROSINA on the Comet 67P/Churyumov-Gerasimenko was the detection of O along with N and noble gases which were measured for the first time in comets, along with the major constituents, water, CO and CO₂. By comparing the experimental results of trapping gases and their relative ratios in the amorphous ice with ROSINA mass spectrometer measurements we can appreciate the gas composition in the comet formation region and the implications for the origin of the volatiles on the solar system (Owen and Bar-Nun, 2000).

Recondensation processes on the surface of Comet P67 nucleus are an indicator of the temperatures variations and the ice composition observed can be simulated on the experiments along with thermal conductivity calculations (Bar-Nun and Laufer, 2003).

More experiments are needed to interpret ROSINA's measurements and also to understand the differences among comets, such as D/H ratios (Altwegg et al., 2015) and origin of the matter forming our solar system (Rubin, M et al., 2017). Laboratory studies are essential also for planning a future sample return mission or deep nuclei excavation.



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(2) Prof. Bar-Nun deceased in January 2017.

SESS03-08: TWINKLE SPACE MISSION – A COMMERCIAL MISSION FOR SPACE SCIENCE

Dr. Marcell Tessenyi^{1,2}, Mr. Max Joshua¹, Professor Giovanna Tinetti^{1,2}, Dr. Georgio Savini^{1,2}, Professor Jonathan Tennyson^{1,2}, Dr. Susan Jason³
¹Blue Skies Space Ltd., London, United Kingdom, ²University College London, London, United Kingdom, ³Surrey Satellite Technology Ltd., Guildford, United Kingdom

Twinkle is a small, dedicated satellite designed to measure the atmospheric composition of exoplanets. Twinkle is a cost-effective spacecraft being built on a short timescale and planned for a launch by 2020. The satellite uses an existing platform designed by Surrey Satellite Technology Ltd, and instrumentation built by a consortium of UK institutes. The mission implementation is based upon a commercial delivery approach that has been successfully applied in other demanding space disciplines.

Twinkle will use visible and infrared spectroscopy to observe the chemical composition and weather of at least 100 exoplanets in the Milky Way, including super-Earths (rocky planets 1-10 times the mass of Earth), Neptunes, sub-Neptunes and gas giants like Jupiter. It will also be capable of follow-up photometric observations of 1000+ exoplanets in the visible and infrared, as well as observations of solar system objects, bright stars and disks.

Blue Skies Space Ltd. is the company managing the Twinkle spacecraft and developing a new model to deliver space science missions for an international science community. This presentation will provide a summary of the mission and the approach taken. For more information visit www.twinkle-spacemission.co.uk

SESS03-09: Q-PACE: A CUBESAT MICROGRAVITY MISSION TO STUDY COLLISIONS IN THE PROTOPLANETARY DISK

Prof. Joshua Colwell¹, Dr. Julie Brisset¹, Prof. Adrienne Dove¹, Mr. Douglas Maukonen¹

¹University Of Central Florida, Orlando, United States

The CubeSat Particle Aggregation and Collision Experiment (Q-PACE) is a long-duration microgravity experiment to study the collisional evolution of small particles in the protoplanetary nebula. Q-PACE builds on results from previous suborbital and ISS payloads that explored the collisional evolution of many-particle systems. The experiment consists of a test cell with a distribution of particles that are induced to collide by a mechanism that shakes the test cell. Collisions between the cell walls and the particles provide starting collision velocities of 5-10 cm/s. The collisional damping of the system is captured on high-frame-rate video by a COTS digital camera for later downlink. The experiment will operate in four distinct phases consisting

of different populations of particles. Each particle population will undergo multiple repetitions of the experiment to build up a large database of collisional outcomes. Models and previous experiments indicate that collisional growth is inhibited beyond the so-called "bouncing barrier" of ~1 cm particles, but that collisional outcomes are largely stochastic, even in carefully controlled experimental settings. Q-PACE will provide a large sample of collisions in a many-particle system to enable a probabilistic description of collision outcomes. Particles will include solid cm-diameter spheres, chondrules from meteorites, mm-scale solid spheres, mm-scale aggregates of micron-sized dust, and micron-sized dust in the final phase of the experiment.

Q-PACE is a 3U CubeSat slated for launch on ELaNax XX in late 2017 with a nominal mission duration of 2 years. The satellite uses PMACS passive attitude control. The duration of a single experiment run is anticipated to be just a few minutes, but due to the high spatial and temporal resolution of the data and the short telemetry contact times and low data rates it will take 1-2 weeks to download the science data from each run. Over the course of the mission we expect to collect data on more than 10,000 particle collisions.

SESS03-10: NATBIO (NATURAL BIOFILM BIOTECH) MISSION OF TEAM KILLALAB: ANALYZING THE SURVIVAL OF BIOFILMS ON LUNAR SURFACE

Mr. Herbert Silva⁵, Mr. Romulo Cruz¹, Mr. Marco Capcha¹, Miss. Sofia Rodriguez¹, Miss. Ruth Quispe¹, Miss. Nohelia Merino³, Mr. Marco Quispe², Mr. Carlos Leonardo¹, Mr. Luis Lizarraga¹, Mr. Jeffrey Ramirez G.⁴, Mr. Victor Vasquez O.⁴

¹Scientific Society of Astrobiology of Perú, Lima, Peru, ²Soluciones Estructurales - STAL Perú, Magdalena del Mar, Peru, ³Centro de Tecnologías de Información y Comunicaciones, Peru, ⁴Universidad Nacional Pedro Ruiz Gallo, Peru, ⁵Stanford University, Stanford, USA

A strong constraint on the settlement of humans in the Moon is the need to launch from Earth the consumables required to sustain crew members. This constraint could be mitigated by in situ resource utilization (ISRU). Some resources such as food, biomaterials, and drugs could be efficiently produced only by biological systems using cyanobacteria. Some cyanobacteria demonstrate significant resistance to gamma radiation and have been shown to survive the desiccating, freezing conditions of space in orbital experiments. Cyanobacteria have great potential for space applications especially in the form of biofilms as they show higher resistance than in planktonic cells.

The Mission NatBio is an interdisciplinary research project of the Scientific Society of Astrobiology of Peru, that will be sent in the spacecraft of the lunar mission of Team Indus on December 2017. Our project was selected from over 1000 projects in a worldwide competition. The research is focused on the effect of space factors on Lunar surface, specifically the ionizing and non-ionizing radiation over the supervivence of biofilms. These biofilms were selected from three different Peruvian sites, and identified as biofilms conformed by cyanobacteria and microalgae. Because aseptic conditions must be maintained throughout the mission, we have developed a biofilm holder with biocompatible materials and sensors that will collect data such as temperature and relative humidity conditions.

The data to be sent from the Moon to Earth will be levels of incident radiation and transmitted radiation, this will allow us to know the radiation levels filtered by the cyanobacteria. We will also be monitoring and recording the data of the reflected radiation analyzed with Nano spectrometers for the identification of the states of the functional groups of photo protectors of biofilms. The Mission NatBio is a miniature "Canlab" that we have designed to be robust and durable for extreme conditions. We are in the process of performing pre-experiments that will consist of simulations and validation for the design.



This will be the first time an experiment from a South American country sends an experiment to the moon. It is our hope that this will inspire other south American groups to get involve in the space exploration sector.

SESS03-11: EQUULEUS: A 6U CUBESAT TO FLY TO LUNAR LAGRANGE POINT ONBOARD SLS EM-1

Assoc. Prof. Ryu Funase¹, Dr. Satoshi Ikari¹, Dr. Yosuke Kawabata¹, Dr. Kota Miyoshi², Shintaro Nakajima¹, Takumi Kudo¹, Yuki Koshiro¹, Masashi Tomooka¹, Shunichiro Nomura¹, Akifumi Wachi¹, Kota Kakihara¹, Ryohei Takahashi¹, Kanta Yanagida¹, Shuhei Matsushita¹, Akihiro Ishikawa¹, Mikihiro Ikura¹, Nobuhiro Funabiki¹, Dr. Yuta Kobayashi², Dr. Atsushi Tomiki², Taichi Ito², Assoc. Prof. Hiroyuki Koizumi¹, Prof. Ichiro Yoshikawa¹, Dr. Hajime Yano², Assoc. Prof. Shinsuke Abe³, Toshinori Ikenaga², Prof. Tatsuaki Hashimoto²
¹University of Tokyo, , Japan, ²JAXA, , Japan, ³Nihon University, , Japan

EQUULEUS (EQUilibrium Lunar-Earth point 6U Spacecraft) will be the world's smallest spacecraft to explore the Earth Moon Lagrange point. The spacecraft will be jointly developed by the University of Tokyo and JAXA and launched by NASA's SLS (Space Launch System) EM-1 (Exploration Mission-1).

The spacecraft will fly to a libration orbit around the Earth-Moon L2 point and demonstrate trajectory control techniques within the Sun-Earth-Moon region (e.g. low-energy transfers using weak stability regions) for the first time by a nano spacecraft. This mission will contribute to the realization of the future efficient cargo transfers to deep space ports located at the Lagrange points. This mission also carries several scientific observation missions/instruments. The first one, named PHOENIX (Plasmaspheric Helium ion Observation by Enhanced New Imager in eXtreme ultraviolet), will conduct the imaging of the Earth's plasmasphere by extreme UV wavelength. The observation will complement and enhance the geospace in-situ observation conducted by the ERG (JAXA's small space science mission launched in 2016) and Van Allen probe (NASA) missions. As a result, we can improve our understanding of the radiation environment around the Earth, which is one of the critical issues for human cis-lunar exploration.

The second scientific observation instrument, named CLOTH (Cis-Lunar Object Detector within Thermal Insulation), will detect and evaluate the meteoroid impact flux in the cis-lunar region by using dust detectors implemented in the spacecraft's MLI (Multi-Layer Insulation). The goal of this mission is to understand the size and spatial distribution of solid objects in the cis-lunar space.

The third scientific observation instrument, named DELPHINUS (DEtection camera for Lunar impact PHenomena IN 6U Spacecraft), will observe the impact flash at the far side of the moon from Earth—Moon L2 point (EML2) for the first time. This observation will characterize the flux of impacting meteors, and the results will contribute to the risk evaluation for future human activity and/or infrastructure on the lunar surface.

EQUULEUS will use X-band and Ka-band frequencies for the deep space telecommunication. Japanese deep space antenna (64-meter antenna and 34-meter antenna) will be nominally used for the spacecraft operation, and the support from DSN (Deep Space Network) of JPL is also being planned. This presentation describes the mission outline, spacecraft system design, and spacecraft development status.

SESS03-12: DEVELOPMENT OF A SIGNAL PROCESSING CIRCUIT OF THE MICROMETEOROID IMPACT SENSOR WITHIN A MULTI-LAYERED INSULATION (CLOTH) ON THE EXTERIOR THE 6U SPACECRAFT EQUULEUS

Mr. Hiroyuki Mochizuki¹, Dr. Takayuki Hirai², Ms. Ritsuko Jitsukawa¹, Mr. Masayuki Fujii³, Dr. Sunao Hasegawa⁴, Mr. Eigo Ishioka¹, Mr. Haruki Nakano¹, Dr. Toshifumi Yanagisawa², Prof. Kazuyoshi Arai¹, Dr. Hajime Yano⁴
¹Hosei University, Tokyo, Japan, ²Japan Aerospace Exploration Agency, Tokyo, Japan, ³FAM Science Co. Ltd., Ibaraki, Japan, ⁴Japan Aerospace Exploration Agency, Kanagawa, Japan

The EQUilibrium Lunar-Earth point 6U Spacecraft (EQUULEUS) is a cube-sat class spacecraft under the development by the University of Tokyo and JAXA. It is one of thirteen secondary payloads for the inaugural launch (EM-1) of NASA's new Space Launch System (SLS). In addition to technology demonstration of low energy trajectory controls of this class of the spacecraft, the EQUULEUS will perform three science missions in its cruising phase and upon its arrival to the Earth-Moon Lagrange point 2 (EML2). Among these, the Cis-Lunar Object Detector within Thermal Insulation (CLOTH) is a polyvinylidene fluoride (PVDF) film sensor for micrometeoroid impacts integrated with its multilayer insulation (MLI) exterior of such a small spacecraft. By turning the spacecraft exterior to effective impact sensor area, the CLOTH can measure meteoroid flux around the EML2 region for the first time.

Thus, the purpose of this study is to develop an impact signal processing circuit for the CLOTH electronics (CLOTH-E). We added integration circuits onto the final stage of its analog signal processing unit in order to improve the accuracy in mass estimate of detected dust particles. Hypervelocity impact experiments were performed for the calibration of CLOTH-E by using the two-stage light gas gun (LGG) at JAXA/ISAS. In the experiments, we shot 100-330 μm particles of soda-lime glass as single projectile at 4-7 km/s. From their calibration data, the dynamic range of CLOTH-E was estimated from 0.06 to 36.3 μm at 12 km/s, the average impact velocity of sporadic dust particles onto the CLOTH sensors.

According to the interplanetary dust flux model at 1 AU, the maximum diameter of dust particles to be detected by the CLOTH sensor area during the nominal EQUULEUS mission lifetime (i.e., one year) was estimated as 30 μm . On the other hand, the minimum detectable diameter which can penetrate the top layer of the MLI to reach to the second-layer PVDF film was estimated as 2 μm by numerical analysis. We then expect that a total number of 2-30 μm diameter grains to be detected would be approximately 48 within an effective exposure area of 635.4 cm^2 .

We also have a capability to detect dust produced by temporary captured orbiters (TCO) in the EML2 region, if any. Due to one order of the difference in impact velocity ranges of these two dust components, we should be able to distinguish one component from the other by measuring on the output voltage from the CLOTH-E.



SESS04a - SCIENCE INSTRUMENTS ENABLING THE NEXT GENERATION OF LOW-COST PLANETARY EXPLORATION

SESS04a-01: ADVANCES IN PLANETARY SEISMOLOGY USING INFRASOUND AND AIRGLOW SIGNATURES ON VENUS

Dr. Attila Komjathy¹, Dr. James Cutts¹, Dr. Michael Pauken¹, Dr. Sharon Kedar¹, Dr. Suzanne Smrekar¹, Dr. Jeff Hall¹, Alan Didion¹, Balthasar Kenda¹, Prof. Jennifer Jackson², Dr. David Mimoun³, Dr. Raphael Garcia³, Prof. Philippe Lognonne⁴

¹NASA JPL, Pasadena, United States, ²Caltech, Pasadena, United States, ³ISAE, Toulouse, France, ⁴IPGP, Paris, France

The planetary evolution and structure of Venus remain uncertain more than half a century after the first visit by a robotic spacecraft. To understand how Venus evolved it is necessary to detect the signs of seismic activity. Due to the adverse surface conditions on Venus, with extremely high temperature and pressure, it is infeasible to place seismometers on the surface for an extended period of time. Due to dynamic coupling between the solid planet and the atmosphere, the waves generated by quakes propagate and can be detected in the atmosphere itself.

JPL in collaboration with ISAE and Caltech Campus is in a process of developing an instrument to measure seismic activity on Venus by in-situ measurements of infrasonic waves in the atmosphere. The overall objective of this research is to demonstrate the feasibility of sensitive barometers to detect infrasonic signals from seismic and explosive activity on Venus from a balloon platform. The seismic signals are known to couple about 60 times more efficiently into the atmosphere on Venus than on Earth, which might allow the detection of small regional quakes (magnitude ~3). We will report results on the first flight experiment that will focus on using the barometer instruments on a tethered helium-filled balloon. The results of the experiments are intended to validate the two-barometer signal processing approach using a well-characterized point signal source.

In addition, we will present another mission concept VAMOS (Venus Airglow Measurement and Orbiter for Seismicity) measuring atmospheric perturbations from an orbiting platform that could provide a breakthrough in detecting seismicity on Venus and in monitoring of seismic surface wave propagation. In contrary to the in-situ balloon strategy, VAMOS will be based on remote airglow monitoring from orbit and might allow to track the propagation of the surface waves and to determine group velocities providing key constraints on crustal and upper mantle structures.

SESS04a-02: INTERPLANETARY AND INTERSTELLAR DUST NEAR EARTH (I2-DUNE): EXPLORING THE VARIABILITY OF THE CHEMICAL MAKEUP OF SOLAR SYSTEM BODIES FROM 1 AU

Dr. Mihaly Horanyi¹, Dr. Eberhard Grün¹, Dr. Antal Juhász², Dr. Sascha Kempf¹, Mr. Marcus Piquette¹, Dr. Andrew Poppe³, Dr. Julie Castillo-Rogez⁴, Dr. Ralf Srama⁵, Dr. Zoltan Sternovsky¹, Dr. Jamey Szalay⁶

¹U. of Colorado, Boulder, Boulder, United States, ²Wigner Institute, Hungarian Academy of Sciences, Budapest, Hungary, ³University of California at Berkeley, Berkeley, USA, ⁴JPL, Pasadena, USA, ⁵University of Stuttgart, Stuttgart, Germany, ⁶SWRI, San Antonio, USA

Interplanetary and interstellar dust particles (IDP and ISD) continually bombard the Earth. They ablate in the atmosphere, and their trajectories

change due to drag forces by the time ground based optical and/or radar observations could fully characterize them. These particles carry valuable information about their parent bodies that can now be fully harvested by in situ dust measurements using newly developed instrumentation to be placed onboard a proposed orbiting spacecraft.

The orbital elements of dust particles that are generated by active comets, by dust impacts onto the surfaces of airless bodies, or by collisions between asteroids, for example, are initially similar to their parent bodies. Collections of such particles form meteoroid streams. Depending on the size of these grains, their initial orbital elements will change and randomize over timescales of centuries or longer, and they become part of the sporadic background of IDPs.

In general, long period Halley-type comets likely come from the Oort Cloud (Tisserand invariant $T < 2$), and short period Jupiter family comets likely originate from the Kuiper Belt ($T > 2$). Main belt asteroids have low inclination, nearly circular orbits. Hence, the orbital elements of the offspring dust particles from comets and asteroids can be used to identify their parents. Interstellar dust particles are entrained in the flow of interstellar gas across our solar system and can be identified by their narrow speed distribution and directionality.

Newly developed dust instruments are capable of measuring the mass, charge, composition, and velocity vector of impacting dust particles, and can be used to explore the chemical variability of our solar system onboard a spacecraft near 1 AU.

This talk will summarize the scientific rationales, measurements, instrument, and mission requirements for I²DUNE.

SESS04a-03: ELECTROMAGNETIC HANDLING OF REGOLITH PARTICLES ON MOON, MARS, ASTEROIDS, AND COMETS

Prof. Hiroyuki Kawamoto¹

¹Waseda University, Tokyo, Japan

Because mitigation and utilization technologies of regolith are critically important for lunar, Mars, asteroid and comet explorations, we are conducting the following research and developments. (1) Electrostatic cleaning of dust on solar panels: We have developed a method of removing dust on solar panels by using an electrostatic traveling-wave generated by a four-phase rectangular voltage applied to a transparent conveyor consisting of parallel ITO (indium tin oxide) electrodes printed on a glass substrate. On the basis of basic investigations, we demonstrated the removal of actual lunar dust using this method. (2) Electrostatic and magnetic cleaners for dust adhering to spacesuits: We have developed three kinds of cleaning systems that utilize electrostatic and magnetic forces. (3) Electrostatic shield for dust entering into mechanical seals of equipment: We have developed a unique shield system for dust by using alternative electrostatic force to prevent dust from entering into bearings and mechanical seals of equipment. In this system, an electrostatic standing-wave is applied to insulated parallel plate electrodes printed on the edges of the gap in the mechanical sealing part. It was demonstrated that more than 90% of the dust was repelled from the gap with the use of very little power. (4) Transport of regolith based on electrostatic traveling-wave and mechanical vibration: A technology for transporting regolith is essential for in-situ resource utilization (ISRU). This transport is realized using an electrostatic traveling-wave and mechanical vibration generated by dielectric elastomer actuators. (5) Electrostatic particle-size classification: Classification of particle size is another important technology required for ISRU. We have developed two technologies that



utilize the balance between electrostatic force and gravitational force for the classification. Our experiment demonstrated that particles less than 20 μm in size could be efficiently separated from the bulk of regolith. (6) Sampling of regolith on the Moon, Mars, and asteroids: To realize reliable and autonomous sampling of regolith on the Moon, Mars, and asteroids, we have developed sampling systems that employ electrostatic and electromagnetic capture and mechanical vibration transport of particles. Experiments demonstrated that substantial amount of regolith is sampled for a short period, even in the 1-G environment on Earth. We also demonstrated the electrostatic capture of particles in a 0-G environment created by the parabolic flight of an aircraft. (7) Electrostatic precipitation in the Martian environment: An electrostatic precipitator was developed to remove dust from the CO₂ gas to be used in ISRU for the production of oxygen in the Martian environment. (8) Manipulation of a single particle: Because micromanipulation of small particles is essential for chemical and physical analyses of captured particles, we have developed an electrostatic manipulator and used it to manipulate particles on the order of 1 μm – 1 mm in diameter.

SESS04a-04: LOW-COST MAGNETOMETER FOR SPACE APPLICATIONS

Leonardo Regoli¹, Matthew Pellioni¹, Mark Moldwin¹, Bret Bronner¹, Kelsey Hite¹

¹University Of Michigan, Ann Arbor, United States

Magnetic fields are ubiquitous in space and getting to measure them in a reliable manner is necessary in order to understand the dynamics of space plasma environments in the whole solar system. For this reason, magnetometers are one of the most important instruments in any spacecraft devoted to the study of planetary magnetospheres, the interaction of the solar wind with non-magnetized objects (such as Venus, Mars or comets) or the propagation of the solar wind in the heliosphere.

Traditionally, space missions have relied on the use of fluxgate and helium magnetometers. While these provide a reliable and well-tested approach to the measurement of magnetic fields, the cost of a single unit can be prohibitive for small spacecraft and CubeSat applications.

We present a novel concept for the measurement of magnetic fields from a commercial off-the-shelf magnetometer based on magnetic induction. Initial characterization of the sensor at the University of Michigan shows the possibility of achieving sub-nT sensitivity and the ability to measure signals with frequencies above 10 Hz. This would enable the sensor to perform measurements of magnetic field topology and magnetospheric waves for a fraction of the cost of a traditional space magnetometer.

SESS04a-05: LOW COST BREAKTHROUGHS IN PLANETARY ATMOSPHERES AND INTERIOR STRUCTURES WITH PRECISION-RADIO-EQUIPPED SMALL SPACECRAFT

Sami Asmar¹, David Atkinson¹, David Bell¹, James Border¹, Ivan Grudin¹, Joseph Lazio¹, Anthony Mannucci¹, Ryan Park¹, Robert Preston¹

¹Jet Propulsion Laboratory, California Institute Of Technology, Pasadena, United States

Radio Science experiments utilizing spacecraft communications links have been conducted on almost every planetary mission in the past five decades and have led to numerous discoveries. With recent technical

advancements, significant accomplishments that fit NASA's themes for planetary exploration included the elucidation of the thermal history of the Moon from the GRAIL high precision gravitational field, the unveiling of interiors of Titan, Enceladus, Mercury, Phobos, Vesta, Ceres, Mars, and cometary nuclei contributing to understanding their origins and particularly providing key evidence for identifying subsurface oceans on icy moons, the sounding of Titan, Saturn, Mars, Venus, and Pluto's atmospheres, and profiling the structure of Saturn's rings. Juno and Cassini experiments are in progress measuring the gravitational fields of Jupiter and Saturn to reveal their interior structures. InSight will soon characterize the Martian core and Akatsuki will further study Venus' atmosphere. Future experiments are planned at Mercury, Jupiter, and other environments.

The cost of Radio Science experiments varies among missions depending on their scientific objectives and the state of the telecommunications capabilities at the spacecraft and ground systems. Some experiments have opportunistically and successfully used mission radio links without additional instrumentation, others have augmented the flight system with Ultra-Stable Oscillators to further advance their scientific capabilities especially for occultations of planetary atmospheres and rings, and yet others have added substantial instrumentation such as dedicated Ka-band transponders and augmented the ground system with specialized equipment for sophisticated calibration techniques.

The community is promoting the utilization of a number of techniques and technologies that would lead in the future to additional significant scientific breakthroughs at relatively lower cost especially as they become part of an infrastructure of commonly available capabilities and services provided by space agencies and industry. Selected science-enabling techniques include laser link science in the era of optical communications, uplink radio occultation as a standard service with specifically enabled transponders, spacecraft-to-spacecraft link instrumentation for rapid planetary coverage and higher signal-to-noise ratio, and the utilization of networks of small spacecraft including planetary CubeSats. Selected science-enabling technologies include advanced precision ranging for Solar System dynamics and tests of General Relativity, a next generation ultra-stable oscillators for small spacecraft, antenna mechanical noise reduction for precision Doppler gravity measurements, and science-based software-defined transponder.

Key to these advanced concepts are science-quality radio links between multiple low cost small spacecraft or mother-daughter spacecraft formation at planetary target configurations that enable the detailed investigations of the planetary gravitational fields and atmospheres. These results, shedding a light at the interior and atmospheric structures, would otherwise not be possible at the same cost.

SESS04a-06: RADIO EMISSIONS FROM ELECTRICAL ACTIVITY IN MARTIAN DUST STORMS

Dr. Shahab Arabshahi¹, Dr. Walid Majid¹, Dr. Dimitrios Antsos¹, Mrs. Cristina Garcia-Miro², Dr. Barry Geldzahler³, Dr. Jonathon Koc⁴, Mr. Tod Schuller⁵, Mr. Leslie White¹

¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, United States, ²Madrid Deep Space Communication Complex, Madrid, Spain, ³National Aeronautics and Space Administration, Washington, United States, ⁴California Institute of Technology, Pasadena, United States, ⁵University of Michigan, Ann Arbor, United States

Dust storms on Mars are predicted to be capable of producing electrostatic fields and discharges, even larger than those in dust storms on Earth. There are three key elements in the characterization of Martian electrostatic discharges: dependence on Martian environmental



conditions, event rate, and the strength of the generated electric fields. The detection and characterization of electric activity in Martian dust storms has important implications for habitability, and preparations for human exploration of the red planet. Furthermore, electrostatic discharges may be linked to local chemistry and plays an important role in the predicted global electrical circuit.

Because of the continuous Mars telecommunication needs of NASA's Mars-based assets, the Deep Space Network (DSN) is the only facility in the world that combines long term, high cadence, observing opportunities with large sensitive telescopes, making it a unique asset worldwide in searching for and characterizing electrostatic activity from large scale convective dust storms at Mars. We will describe a newly inaugurated program at NASA's Madrid Deep Space Communication Complex to carry out a long-term monitoring campaign to search for and characterize the entire Mars hemisphere for powerful discharges during routine tracking of spacecraft at Mars on an entirely non-interfering basis. The ground-based detections will also have important implications for the design of a future instrument that could make similar in-situ measurements from orbit or from the surface of Mars, with far greater sensitivity and duty cycle, opening up a new window in our understanding of the Martian environment.

SESS04a-07: THE EUROPA IMAGING SYSTEM (EIS): A CAMERA SUITE TO INVESTIGATE EUROPA'S GEOLOGY, ICE SHELL, AND POTENTIAL FOR CURRENT ACTIVITY

Dr. Elizabeth Turtle¹, **Dr. Wes Patterson**¹, Dr. Alfred McEwen², EIS Team
¹Johns Hopkins Applied Physics Laboratory, Laurel, United States, ²Univ. Arizona, Tucson, United States

The Europa Imaging System (EIS) being built for NASA's Europa Clipper Mission is a camera suite designed to provide global decameter-scale coverage, topographic and color mapping, and unprecedented sub-meter-scale imaging during rapid, low-altitude flybys. EIS combines narrow-angle and wide-angle cameras (NAC and WAC) to address broad science objectives:

- Constrain formation processes of surface features by characterizing geologic structures, surface units, global cross-cutting relationships, and relationships to subsurface structure and potential near-surface water.
- Search for evidence of recent or current activity, including potential plumes.
- Characterize the ice shell by constraining its thickness and correlating surface features with subsurface structures detected by ice penetrating radar.
- Characterize scientifically compelling landing sites and hazards at meter-scales.

The NAC, derived from New Horizons LORRI heritage, has a 2.3° cross-track x 1.2° along-track field of view (FOV) and 10- μ rad instantaneous FOV (IFOV) to achieve 0.5-m pixel scale over a 2-km-wide swath from 50-km altitude. It is mounted on a 2-axis $\pm 30^\circ$ gimbal to enable targeting independent of S/C pointing, making near-global mapping of Europa possible at ≤ 50 -m pixel scale, as well as regional stereo imaging. The gimbal slew rate is designed to be able to perform very high-resolution stereo imaging from as close as 50-km altitude during high-speed (~ 4.5 m/s) flybys, generating digital topographic models (DTMs) with 2-m spatial scale and 0.25-m vertical precision over the 2-km swath. The NAC will also perform high-phase-angle observations to search for potential plumes; with a pixel scale of 10 km from a range of 1,000,000 km, the NAC can take advantage of good illumination geometry for forward scattering by potential plumes even when the spacecraft is distant from Europa.

The WAC, derived from MESSENGER MDIS heritage, has a 48° cross-track x 24° along-track FOV, with 218- μ rad IFOV. The along-track FOV is designed to provide sufficient convergence angle to acquire pushbroom stereo swaths along flyby ground-tracks. From 50-km altitude, the WAC achieves 11-m pixel scale over a 44-km-wide swath, generating DTMs with 32-m spatial scale and

4-m vertical precision. These data also support characterization of surface clutter for interpretation of radar sounding profiles.

The cameras have identical radiation-hard 4k x 2k CMOS detectors which function in both pushbroom and framing modes, and have rapid readout for imaging during fast flybys and to minimize radiation-induced noise. Color observations are acquired by pushbroom imaging with six broadband stripe-filters. Each camera also has a radiation-hardened data processing unit (DPU) that takes full advantage of the rapid, random-access readout of the CMOS arrays to perform innovative real-time processing for pushbroom imaging, including WAC 3-line stereo, digital time-delay integration (TDI) to enhance signal-to-noise ratio, and readout strategies to measure and correct pointing jitter.

The capability and flexibility of the EIS camera suite make the design broadly applicable to missions to a variety of planetary targets. For example, the fast flyby imaging and rad-hard design make EIS well suited to an Io mission in Discovery or New Frontiers. The low-power focal plane system could be useful on some smallsat concepts.

SESS04a-08: FLEXIBLE CAMERA ARCHITECTURE FOR GENERIC SPACE IMAGING APPLICATIONS

Dr Christophe Basset¹, Colin McKinney¹, Mark Schwochert¹, **Robert Staehle**¹, Dr Justin Boland¹

¹Jet Propulsion Laboratory, Pasadena, United States

The implementation of space-borne engineering and science imaging has historically required costly, fully-custom designs and development in order to succeed in the extreme operating environments of NASA missions. Wide-temperature operation and survival, radiation tolerance, and extended performance lifetime requirements resulted in large capital investments in custom imaging sensors, optical assemblies, packaging approaches, and qualification testing. Such custom developments routinely incur schedule risks or delays for advancing Technology Readiness Levels (TRL) and meeting demanding project delivery timelines. We have developed an adaptable camera platform that takes advantage of screened and qualified commercial off the shelf (COTS) components to significantly shorten development time while reducing the overall cost and risk of the design. To date, this modular camera platform has been infused on two Class-D camera systems at NASA's Jet Propulsion Laboratory (JPL)—NEAScout and the Orbiting Carbon Observatory (OCO-3) Context Cameras—and can be tailored to meet the cost, schedule, and performance envelopes of major mission concepts, CubeSats, and SmallSats for future proposals.

As part of the Mars 2020 program, a new enhanced engineering camera (EECam) was developed at JPL to fulfill the need for an upgraded visible-light imaging system aboard NASA's next Mars rover. This camera system is a follow-on to the highly successful engineering cameras (ECAM) developed for the Mars Exploration Rovers (MER) and re-flown on the Mars Science Laboratory (MSL), Phoenix Lander, and InSight lander (scheduled for launch in 2018), and now as SkyCam for Mars 2020's Mars Environmental Dynamics Analyzer (MEDA). As part of the necessary screening and qualification for the EECam Class B hardware, the Mars 2020 program invested resources in screening COTS parts to evaluate packaging ruggedness, radiation sensitivity, and lifetime performance to meet mission requirements.

Several of JPL's smaller spacecraft missions are taking advantage of the qualification work performed by Mars 2020 by reusing the screened COTS imaging sensor, proven electronic designs, and scalable field-programmable gate array (FPGA) firmware to meet tailored mission



requirements and lower resource availability. Larger Discovery or New Frontiers-class mission concepts may also benefit by leveraging the Mars 2020 build-to-print design to reduce risk and schedule. A hardware platform was created for the OCO-3 Context Cameras consisting of three compact electronic boards, a high-resolution COTS image sensor, a radiation-hard FPGA, custom aluminum chassis, and two ruggedized COTS C-mount lenses. This design has since been re-used and tailored to meet the low cost cap of the NEAScout CubeSat mission. Modifications included a new COTS optical system using the standard C-mount, different electrical data interface protocol, and mechanical chassis modifications. These changes were easily and quickly integrated within a constrained CubeSat budget, highlighting the flexibility of the system.

We will be presenting the steps taken by JPL to select and design a camera architecture that is being used as a base for incorporation into mission concepts for low-cost planetary exploration. We will also explore possible customization options and the trade-offs of adapting the platform to specific requirements and environments, in terms of technical challenges, mission risk, and impact to a project's schedule and cost.

SESS04a-09: THE ADVANCED MULTISPECTRAL INFRARED MICROIMAGER (AMIM) FOR FUTURE IN SITU EXPLORATION OF PLANETARY SURFACES

Dr. Jorge Núñez¹, Dr. Rachel Klima¹, Dr. Scott Murchie¹, Mr. John Boldt¹, Dr. Heidi Warriner¹, Dr. E. H. Darlington¹, Mr. Matthew Bowers¹, Mr. Bryan Maas¹

¹Johns Hopkins University Applied Physics Laboratory, Laurel, United States

Future low-cost planetary missions to the surfaces of the Moon, Mars, asteroids, comets, and Ocean Worlds will need instruments that can maximize scientific return, but maintain low mass, size, and power that can be accommodated on mass and power-constrained landers or rovers. We are developing the Advanced Multispectral Infrared Microimager (AMIM) - a compact microscopic imager that will be able to provide in situ spatially-correlated mineralogical and microtextural information of rocks and soils at the microscale - for future planetary missions to enable geological interpretations and infer potential habitability of planetary surfaces, support traverse characterization, and facilitate the selection of samples for onboard analysis with other instruments.

AMIM consists of a novel LED-based illumination system composed of compact, low-power multispectral LED arrays coated with narrow-bandpass filters, an adjustable focus mechanism capable of imaging near and far, and a visible/infrared camera capable of imaging from the visible/near-infrared to shortwave-infrared (VNIR/SWIR, 0.4 to 2.6 μm ; expandable to 4 μm). By imaging in the VNIR/SWIR, AMIM is particularly well-suited for detecting and mapping Fe-bearing igneous and oxide minerals (such as olivine or hematite), carbonates, OH/H₂O-bearing minerals (such as clays or sulfates), and ices (such as H₂O and CO₂). These minerals are of cross-cutting importance in planetary science, because some or all of them are found on the surface of the Moon, Mars, asteroids, comets, and Ocean Worlds, and are indicative of past and/or present geologic processes.

AMIM advances beyond the capabilities of current 3-band imagers in the visible (RGB) or multispectral imagers that operate in the VNIR (0.4-1.0 μm), which are limited to detecting Fe-bearing minerals. The expanded coverage in the SWIR and narrow bandpasses (FWHM < 50 nm) enable AMIM to discriminate both iron and non-iron bearing mineralogies with greater fidelity compared to these instruments or similar imagers with wider bandpasses (> 100 nm). By employing a compact, low-power illumination system, AMIM eliminates the need for mechanical or

complex systems such as a filter wheel, grating system, scan mirrors, multiple detectors, or tunable filters. This reduces the mass, size, power consumption, and complexity of the instrument enabling it to be deployed at the end of a robotic arm on a compact rover or lander. Thus, AMIM would provide many of the capabilities that are commonly associated with orbital instruments such as CRISM on the Mars Reconnaissance Orbiter (MRO) or M3 on Chandrayaan 1, but at a size and mass comparable to current microscopic imagers for landed science - a capability unmatched by any current microimaging instrument developed for flight.

SESS04a-10: A SMALLSAT-BASED THERMAL IMAGER WITH HIGH ACCURACY MULTIPLE SOURCE CALIBRATION SYSTEM

David Osterman¹, Reuben Rohrschneider, Robert Warden, Sandra Collins, John Ferguson, Alfonso Amparan, Mike Adkins, Thomas Kampe

¹Ball Aerospace, Boulder, United States

CIRiS (Compact Infrared Radiometer in Space) is a thermal infrared imaging instrument designed for imaging scene temperatures with high absolute and relative accuracy from a small, 6U volume spacecraft. The instrument utilizes a fold mirror to rotate the field of view, without varying reflection angles, between the science scene and one of three calibration scenes. The latter consist of views to one ambient-temperature blackbody source, a second source at a selectable temperature and deep space. The capability to view deep space on command provides a useful temperature reference for cryogenic planetary surfaces. Combinations of calibration views enable optimization for scene temperatures over specific ranges of interest. The CIRiS blackbody sources are substrates with carbon nanotube films whose high emissivity ($\epsilon > 0.996$ in the thermal infrared) reduces stray light reflections, thereby improving calibration accuracy. Components bolt on to a central structural cube, facilitating the independent customization of the telescope, baffles and other elements for specific missions. The uncooled infrared focal plane array is a factor in fitting the entire instrument, including electronics, in the 6U envelope. Memory on the single electronics board stores image frame data for periodic transmission to spacecraft memory. A version of CIRiS integrated into a CubeSat is presently in the assembly phase for a technology demonstration mission in Low Earth Orbit, with launch planned for 2018.

SESS04a-11: A LOW COST FAR-UV MISSION CONCEPT FOR PLANETARY SCIENCE

Dr. Philippa Molyneux¹, Dr Kurt Retherford¹, John Scherrer¹, Dr Mark Tapley¹, Dr Michael Davis¹

¹Southwest Research Institute, San Antonio, United States

Planetary missions are typically more challenging for propulsion, power and communications than Earth orbiting science missions. With the success of the low cost, class D NASA Earth Sciences Cyclone Global Navigation Satellite System (CYGNSS) mission, this paper looks at adapting the lessons learned from CYGNSS to overcome these obstacles and translating them to low cost Planetary Science. The mission concept of a UV mission to investigate lunar water ice and surface hydration was used as the design test point. Remote sensing in the far ultraviolet (FUV) spectral region is a proven, valuable technique for solar system science, allowing detailed characterization of planetary surfaces, atmospheres and auroras. Recent discoveries utilizing the FUV region include the tentative detection of plumes at Europa by the Hubble Space Telescope (Roth et al., 2014; Sparks et al., 2016), the detection and characterization of an atmosphere and plumes at Enceladus by Cassini UVIS (Hansen



et al., 2006, 2008, 2011), and albedo measurements of the Moon's permanently shaded regions (PSRs) by the Lunar Reconnaissance Orbiter (LRO) Lyman Alpha Mapping Project (LAMP) (Gladstone et al., 2010, 2012). The development of a compact FUV instrument and platform would extend access of this important spectral region to small, low cost planetary missions. An added capability for wide field imaging at FUV wavelengths would provide improved spatial coverage at higher cadence, allowing better characterization of time-variable signals and enabling, for example, diurnal and seasonal changes in the hydration of the lunar PSRs, or short-timescale dynamics of planetary atmospheres and auroras to be investigated. We therefore describe an FUV imager concept with a 40° field-of-view and 0.45° resolution (Davis et al., SPIE, 2014). We explore potential science questions the instrument could address and discuss the low cost mission concepts for which it would be best suited, with a focus on lunar surface imaging applications building on experience gained from LRO-LAMP.

SESS04a-12: NEW GENERATION OF COMPACT COMETARY D/H SURVEY MISSION

Dr. Sona Hosseini¹, Dr. Bjorn Davidsson¹, Dr. Kathrin Altwegg², Dr. Robert West¹, Dr. Konstantinos Giapis³

¹JPL- Caltech, Pasadena, United States, ²University of Bern, Bern, Germany, ³Caltech, Pasadena, United States

There are numerous debates and models about the source of water and organic compounds on Earth and other terrestrial planets without converging to an agreement. One of the best ways to study this problem is by determining the deuterium-to-hydrogen (D/H) ratios in comets and across the Solar System because there is a gradient in D/H in the solar nebula due to the temperature gradient. The OD/OH in interstellar space measurements is usually around 2×10^{-5} , slightly higher than the Earth's 1.5×10^{-4} value. The previous notion was that Jupiter family comets (JFC) are formed further away from the Sun, close to Neptune, whereas Oort cloud comets have formed closer in, outside of Saturn. If that proposition is correct, then we should see a trend of higher D/H ratio in JFCs than the Oort cloud comets. This hypothesis, however, is under debate due to mixing values of D/H measurements in JFCs. The first D/H of a JFC with Hartley 2 had a terrestrial value and opened the considerations to formulate mechanisms on why JFC's had lower D/H. This debate continued with the recent direct in situ measurement of $D/H = 5.3 \times 10^{-4}$ in another JFC comet, 67P, value three times higher than Earth. This hypothesis could mean that there is high variability in the positioning of these comets. Our very few cometary D/H measurements suggest a wide range of D/H ratios in the water within Jupiter family objects and preclude the idea that this reservoir is solely composed of Earth ocean-like water. We need not one, or two but several measurements of many comets, as well as several temporal observation of many comets over the period of their orbit around the sun and preferably data from the same comets over multiple orbits before we can apply statistics and improve our ability to distinguish between different scenarios. It is not possible to get such statistics using in situ measurements, such as mass spectrometers, and the current remote sensing high spectral resolution spectrometers require large aperture space-borne telescopes that can't be solely dedicated to cometary studies.

We are proposing to take advantage of a novel technique, Spatial Heterodyne Spectrometer (SHS), to survey cometary D/H in 308 nm in NUV region. SHS is a high throughput, a reflective two-beam cyclical interferometer that can obtain high spectral resolution spectra ($R \sim 100,000$) from a narrow bandpass in VIS to UV in a miniaturized format using small aperture telescopes. A key advantage comes in achieving high sensitivity (R) observations using small (<0.5m) aperture telescopes in a dedicated SmallSat. Using SHS in a low cost (<\$50M) SmallSat in a polar orbit

around the Earth, SHS will enable us to survey cometary D/H ratio in many comets as a function of heliocentric distance as they enter the Solar System and exit. Also, depending on the activity levels, we will be able to study Jupiter family comets in multiple orbits. No other approach provides this capability in a compact and mechanically stable configuration.

SESS04b - TECHNOLOGY AND ENGINEERING DEVELOPMENTS ENABLING THE NEXT GENERATION OF LOW-COST PLANETARY EXPLORATION

SESS04b-01: CHARACTERIZATION OF PLANETARY ATMOSPHERIC DYNAMICS BY DOPPLER TRACKING OF A CONSTELLATION OF SMALL ENTRY PROBES

Dr. David Atkinson¹, Mr. Sami Asmar¹, Dr. Joseph Lazio¹, Dr. Robert A. Preston¹

¹NASA/Caltech Jet Propulsion Laboratory, Pasadena, United States

The characterization of the dynamics of the atmosphere of a solar system body is an important element in understanding the overall structure of the atmosphere. The efficacy of Doppler tracking of entry probes for the in situ retrieval of wind fields has been successfully demonstrated multiple times at Venus with Venera, VEGA, and Pioneer, and more recently at Jupiter and Titan with the Galileo and Huygens probes, respectively. However, in all but one case (Pioneer Venus), the vertical profile of zonal winds was retrieved along the descent path of only a single probe. For a more complete understanding of a planet's or moon's circulation and dynamical structure, near-simultaneous wind measurements at multiple locations are needed. Of particular importance is the variation of winds at different latitudes and correspondingly different solar insolutions, and diurnal changes at different longitudes/time of day. Potential targets in the solar system for new atmospheric multi-probes includes Jupiter, Saturn, Titan, Uranus, Neptune, and Venus.

The accuracy of Doppler wind retrievals is limited by the stability of both the on-board clock used to generate the probe telemetry signal and the receiver clock that is measuring the received signal frequency, and by the accuracy of the probe descent location and speed reconstruction. On-board measurements of atmospheric pressure and temperature during descent is used to determine probe descent speed, thereby removing one vector component of the probe motion. The remaining Doppler residuals will then be due to the horizontal winds alone. If the signal from each probe can be simultaneously received by the carrier spacecraft as well as from a second spacecraft or from Earth, east-west vs. north-south components of the horizontal winds can be separated. Multiple small probes independently targeted to enter and descend through a planet's or moon's atmosphere at widely separated latitudes and longitudes can provide a more complete global characterization of a planet's atmospheric dynamics and overall circulation. Each probe would be equipped with a parachute system providing a controlled terminal descent speed, a transmit-only telecomm system including a small ultrastable oscillator with an Allan Deviation of $\sim 10^{-13}$ (100 seconds), and atmospheric structure sensors to measure atmospheric pressure and temperature. Including both dynamic and static pressure sensors permits the body-centered and atmosphere-relative descent speeds to be determined, thereby offering the capability of measuring vertical motions due to convection or atmospheric waves.



SESS04b-02: APPLYING MODEL PREDICTIVE CONTROL ARCHITECTURE FOR EFFICIENT AUTONOMOUS DATA COLLECTION AND OPERATIONS ON PLANETARY MISSIONS

Mr. Mike Lieber¹, Dr Eric Schindhelm¹, Dr Reuben Rohrschneider¹, Dr Carl Weimer¹, Dr Shane Roark¹

¹Ball Aerospace, Boulder, United States

Low-cost Planetary Science missions stand to benefit from recent developments in miniaturization of satellite technology (e.g. CubeSats) and increased on-board automation. Whether utilizing onboard processes to automate instrument and spacecraft operations or to controlling a network of smallsats, balloons, or rovers, automation can optimize both power utilization and the science data collection process. Through NASA-ESTO funding, we are developing algorithms supporting optimizing data collection from space using an architecture based upon Model Predictive Control (MPC). MPC is an ideal framework for autonomous, real-time control of complex systems because it re-optimizes with respect to multiple goals and constraints at every time step. Because of this proven capability, it is often the starting point for software control architecture design of many terrestrial applications including autonomous cars, robotic vision systems and it has been proposed for control of distributed spacecraft. In this presentation we expound upon both the fundamentals of the MPC-based approach with its ability to incorporate hierarchical and distributed elements and also the computational challenges. We then present some results of laboratory testing and software validation for a targeted application - an adaptive, multi-beam lidar remote sensing platform. The software has been demonstrated to a Technology Readiness Level (TRL) 4 for the adaptive lidar, but because of the top-down approach, can be readily re-purposed to adaptive real-time control for multiple instruments and spacecraft around planetary bodies. Beyond the targeted application, MPC provides an architecture for controlling formation flying CubeSat swarms performing unique surface or atmospheric measurements, or tiered systems of platforms for remote exploration. Onboard science operations can be automated to direct collection, prioritization, compression, and downlink of data. We will speak specifically to utilizing MPC with adaptive lidar for planetary science applications such as studying surface topography and changes or optimizing lander placement through vision navigation sensors.

SESS04b-03: LANDING DYNAMICS OF TWO-STEP LANDING METHOD FOR SMALL LUNAR-PLANETARY LANDER

Mr. Shunpei Morikawa¹, Mr. Hikaru Eguchi², Prof. Yusuke Maru³, Mr. Taro Kawano³, Prof. Masahiro Nohmi¹, Prof. Shujiro Sawai³

¹Shizuoka University, Sagamihara, Japan, ²The Graduate University for Advanced Studies, Sagamihara, Japan, ³Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan

For future exploratory mission, the spacecraft is required to land near exploratory objects. Kaguya (SELENE) which was a lunar orbiter in JAXA obtained scientific data. Consequently, interests in the moon and demand to explore various sites of the moon in detail are more increasing. In order to meet this demand, a novel landing method or gear is required, because these landing sites may be rough sites. Conventional planetary exploration spacecraft landed on level terrain securely. So, a conventional landing method and gear may give a risk of the lander's overturning if the lander lands on a rough site.

Recently, small lunar-planetary exploration spacecraft are developed. ISAS/JAXA proposed small experimental spacecraft named as "SLIM".

Developing costs and terms of SLIM are reduced by making the lander compact and lightweight. This effort can contribute to make future lunar and planetary exploration frequently.

On the other hand, compact and lightweight exploration spacecraft have a trouble concerning landing stability. If a regulation of a lander's size and weight is not strict, a gear to enhance lander's landing stability can be attached. But compact and lightweight exploration spacecraft is needed to be designed considering constrain of the lander' weight and a launch vehicle.

Therefore, we need a novel landing method of high landing stability, which is applicable to small lunar and planetary exploration spacecraft. So, we propose a novel landing method called "Two-step landing method". The lander which adopt the proposed method have primary legs and assisting legs with skids. In the sequence of the proposed method, the lander fall with body attitude tilted, and primary legs contact with planetary surface and the body is forced to tumble intentionally. Eventually, assisting legs bear the lander's weight.

This study discusses landing characteristics of Two-step landing method by numerical simulation. Numerical simulation models have been designed on Mechanical Dynamics Software "ADAMS", and lander models refer to SLIM. In order to examine characteristics of the method, parameters including lander's initial attitude and velocity, the number of primary legs and slope angle of landing site are considered, and landing success or failure is examined for each case. Simulation results show that the proposed method can land on steep slope by tilting body attitude toward inclination direction of a landing site. In addition, we examine characteristics of the proposed method by drop test using 1/3 scale modules which also refer to SLIM.

SESS04b-04: SATURN SWARM STUDY

Mr. Andrew Blocher

¹California Polytechnic State University, United States

The Cassini Mission has made countless discoveries at Saturn furthering our knowledge of the Solar System formation and finding new ocean worlds that might have the possibility of supporting life. But as the mission ends, questions remain and even more have risen. To answer these questions, JPL has considered 3 missions for the recent New Frontiers opportunity. The missions range from probing Saturn's interior to exploring the ocean worlds of Titan and Enceladus. With the down selection for Phase A studies, it is anticipated that NASA may consider proposals for Technology Demonstration Options (TDOs) to accompany the primary New Frontiers spacecraft. Ten TDO concepts have been conceived that could accompany one of the primary spacecraft to Saturn and perform unique and ground breaking science as well as demonstrate new technologies.

In LEO, SmallSats and CubeSats have changed the exploration paradigm, offering a fast and low cost alternative to traditional space vehicles. These small spacecraft have spawned revolutionizing industries and are performing cutting edge science. This new mission development philosophy has the potential to significantly change the economics of interplanetary exploration and a number of missions are in development that utilize CubeSat class spacecraft beyond Earth orbit, including NEAScout, Lunar Ice Cube and MarCo.

The ten TDO concepts for exploring the Saturn system would take advantage of advances in Small/CubeSat technology, demonstrating their ability to be used outside the traditional confines of LEO. New technology and instruments would also be demonstrated for use in future missions. The TDOs demonstrate the technologies while advancing scientific



knowledge with investigations ranging from Venus atmospheric in situ measurements to close up examination of Saturn's rings, from stereo mapping of the south pole of Enceladus, to characterizing the interaction of the magnetosphere with the solar wind.

SESS04b-05: FLEXIBLE THREE PHASE BRUSHLESS DC MOTOR DRIVER FOR MEDIUM RADIATION LEVEL

Mr. Hans-Juergen Sedlmayr, Mr. Maximilian Maier, Dr. Josef Reill, Mrs. Friederike Wolff

¹DLR, Wessling, Germany

Robotic systems can provide an excellent on-site or remote support for astronauts during routine tasks and perform even autonomous tasks during exploration missions.

New systems like the robotic arm CAESAR, the four-fingered robotic hand Spacehand, small exploration systems like MASCOT or several Pan-Tilt-Units on rovers emphasize the need for a highly integrated, high-performance motor controller with a small footprint.

This paper presents a cold redundant, three Phase brushless DC Motor Driver for medium radiation levels which was developed at the Institute of Robotics and Mechatronics of the German Aerospace Center (DLR). This module is able to withstand 120W of continuous motor power, offers interfaces for analogue and digital motor position measurements as well as a standard high level communication interface on a single board with an extremely small footprint.

Due to its small footprint, multiple boards could be used within a robotic system to drive multiple motors synchronously. Simulations have been performed to show the increase in performance that can be achieved through the simultaneous motion of multiple actuators. A potential application is MASCOT-2 (Mobile Asteroid Surface Scout), which is analyzed as a case study to present the benefits of a multi-actuator system for relocation and attitude control in low-gravity environments.

SESS04b-06: COMBUSTION JOINING OF REGOLITH TILES FOR THE IN-SITU FABRICATION OF LAUNCH/LANDING PADS ON THE MOON AND MARS

Mr. Robert Ferguson¹, Dr. James G. Mantovani², Dr. Evgeny Shafirovich¹

¹The University of Texas at El Paso, El Paso, United States, ²Granular Mechanics and Regolith Operations Lab, Kennedy Space Center, USA

To mitigate dust problems during launch/landing operations in lunar and Mars missions, it is desired to build solid pads on the surface. Recently, strong tiles have been fabricated from lunar regolith simulants using high-temperature sintering. The present work investigates combustion joining of these tiles through the use of exothermic reactions. Based on thermodynamic calculations, it is hypothesized that combustion of a stoichiometric nickel/aluminum mixture in the gap between the tiles will weld the regolith tiles together. The objective is to experimentally determine the minimum distance between two regolith tiles that is needed for the formation of a strong weld through a self-propagating combustion of the intermetallic mixture. The mixture, placed in the gap between tiles fabricated from JSC-1A lunar regolith simulant, is ignited by a CO₂ laser in an argon environment. The combustion front propagation over the mixture is studied using video recording.

SESS04b-07: ASSEMBLY OF STRUCTURES ON THE SURFACE OF THE MOON BY SELF-ORGANIZED ROBOTS

Dr. Gustavo Medina-Tanco¹

¹Institute of Nuclear Sciences, UNAM, Ciudad De Mexico, Mexico

We present here a proof of concept mission for demonstrating the feasibility of assembling significant structures using a self-organized set of robots. The main idea is that a swarm of small robots can be used in the future as an accessory in tackling the challenge of building adaptive structures on hostile asteroidal or planetary environments, where detailed surface features are unknown a priori. The robots are incorporated as an active constituent of the final structure. There is no central coordination and the main guidelines for the structure are built into the interaction laws that rule the evolution of the robots. In other words, the structure is an emergent property of the interacting system. The mission will be carried out on the surface of the Moon by an ensemble of nine small robot with a typical scale size 1/10th of the Debye length of the dusty surface plasma. The mission is being developed under the responsibility of the Laboratory for Space Instrumentation of the Institute of Nuclear Sciences at UNAM, México, with the support of CONACyT and the Mexican Space Agency. It is planned for flight on 2019 onboard the Peregrine lander from Astrobotic.

SESS05 - ADVANCED CONCEPTS FOR THE NEXT GENERATION OF LOW-COST MISSIONS, INCLUDING CUBESATS, NANOSATS AND OTHERS

SESS05-01: AN INTERPLANETARY CUBESAT MISSION TO PHOBOS

Prof. Jekan Thanga^{1,2}, Prof Erik Asphaug¹, Graham Dektor¹, Nalika Kenia¹, James Uglietta¹, Shota Ichikawa¹, Akshay Choudhari¹, Mercedes Hereras-Martinez¹, Dr. Stephen Schwartz¹

¹Arizona State University, Tempe, United States, ²University of Alabama, Huntsville, Huntsville, United States

Martian moon Phobos may hold vital clues to the origin of Mars. The moons exhibits several unique features such as surface striations due to being within the Mars Roche limit. Phobos has been suggested as a low delta-v stop-over site and staging base for human missions to Mars. Considering Phobos maybe a strategic location for future Mars human exploration, little is known about the moon's origin, composition and surface-properties. This data is critical towards designing a feasible missions with the eventual goal of developing a staging base on Phobos. To date, missions with a major Phobos focus have all failed prematurely.

With this in mind, there is an important need to have a dedicated suite of missions to Phobos. JAXA's MMX mission offers the best chance yet. CubeSats could complement missions like MMX and offer the opportunity to perform low-cost, higher-risk focused science exploration, with rapid turn-around times between multiple missions. A credible option is to have multiple small spacecraft that focus on simple tasks instead of a single, large spacecraft with multitasking functions. For those reasons, it is a reasonable option to utilize CubeSats as a stepping-stone to answering specific questions about Phobos, uncovering its mysteries and contributing towards long-term human exploration of Mars. We propose development of a 6U, 14 kg interplanetary CubeSat called LOGIC (Low Orbit Geology Imaging CubeSat) that would be performing thermal and visible imaging of Phobos at resolutions of 25 m/pixel and 5 m/pixel respectively. LOGIC is inspired by JPL's INSPIRE and MarCO CubeSats.



This CubeSat mission would be a pathfinder towards a larger suite of missions. This CubeSat mission to Phobos would provide an unprecedented view of the moon, including coverage of more than 50 % of the surface. The spacecraft will obtain detailed images of striations, crater rims, surface boulders and material composition. The spacecraft contains two science instruments, namely the e2V Cires Visible camera and FLIR Tau thermal camera. The spacecraft is powered using a pair of onboard deployable solar panels, eHawk+ from MMA Design. The back side of the solar panels contains an X-band reflect-array for communication and will utilize JPL's IRIS v2.1 X-band radio. The spacecraft will utilize BCT XACT attitude determination and control system. The spacecraft will be deployed on a Mars flyby trajectory and be propelled using a green monopropellant system developed by Aerojet Rocketdyne. Green monopropellant provides the most practical option for a high-thrust, high delta-v CubeSat propulsion system. The spacecraft will enter into a highly elliptical orbit, then perform aerobraking to enter into a co-orbit with Phobos.

Interplanetary CubeSats offer a compelling path forward towards short, focused science missions that act as pathfinders and support assets for larger, long-term missions. Even if one fails, a CubeSat mission maybe assembled with a relatively short turn-around time. Phobos is an excellent target to better understand small-bodies, the origin and composition and is critical for making a future human mission to Mars a reality.

SESS05-02: DEEP SPACE 9 MISSION CONCEPT - SECONDARY PAYLOAD STUDY FOR THE PROPOSED NEXT MARS ORBITER

Tod Schulter¹, Adrian Arteaga¹, Robyn Hinchman¹, Tzu-Hsiang Lin¹, Nate Williams¹, Tatiana Roy¹, Athip Thirupathi Raj¹, Sanskar Bhattacharya¹, Ajit Bhat¹, Bogdan Oaida², Danielle Marsh², Austin Nicholas², Serina Diniega²

¹University Of Michigan, Ann Arbor, United States, ²Jet Propulsion Laboratory, California Institute of Technology, Pasadena, United States

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

The hypothetical DS9 constellation would consist of four 6U CubeSats in low-Mars orbit that image the surface and atmosphere of Mars in nine spectral bands, and two 3U CubeSats in high-Mars orbit to enable radio occultation sounding of the atmosphere by transmitting to the CubeSats below. These observations would enable the characterization of the processes that control the distribution of dust and volatiles in the lower atmosphere as well as define the mechanisms by which these exchange between the surface and atmosphere. Furthermore, they would help determine the characteristics of the atmosphere that affect EDL designs and that may pose a risk to ascent vehicles, ground systems, and human

explorers. Successful completion of these science objectives would further NASA's goal of characterizing the state of the present climate of Mars' atmosphere and its underlying processes, as well as the goal of obtaining knowledge sufficient to design and implement a human mission to the Martian surface within acceptable cost, risk, and performance parameters. Lastly, the mission concept would utilize mostly COTS parts and an updated version of the high-heritage Mars Color Imager (MARCI) instrument as the principal science payload. In doing so, Deep Space 9 would accomplish its objectives within minimal cost and risk levels.

Note: This is predecisional information for planning and discussion only.

SESS05-03: RADIO OCCULTATION MISSION TO MARS USING CUBESATS

Dr. Walton Williamson¹, Dr Anthony Mannucci¹, Dr. Chi Ao¹
¹Jet Propulsion Laboratory, Pasadena, United States

JPL is developing cubesat technology for the purpose of planetary radio occultation experiments. Radio occultations have been used since the early Mariner missions to characterize the atmospheric properties of Venus and other planets. The proposed mission would provide global coverage around Mars for at least one Martian year using multiple cubesats stationed at Mars. This paper will present the mission concept, instrument design, and science return for a mission of three cubesats.

SESS05-04: MARS DARTDROP: PROBING CONTEMPORARY HABITABILITY AT RECURRING SLOPE LINEAE

Robert Grimm¹, David Stillman¹, Robert Staehle², Matthew Eby³, Gregory Dirks¹, David Ruggles¹, Aaron Zent⁴

¹Southwest Research Institute, United States, ²Jet Propulsion Laboratory, ³Aerospace Corporation, ⁴NASA Ames Research Center

Recurring slope lineae (RSL) are dark, narrow features on Mars that incrementally lengthen during warm seasons, fade away in cold seasons, and recur each year. While RSL have been widely considered to be seasonal liquid water at (or just below) the surface of Mars, other theory and evidence suggest they could be debris flows. Understanding the true nature of these features is pivotal to questions of the contemporary habitability of Mars and its impact on future robotic and human exploration. We have devised DartDrop, whose principal scientific objective is to determine the habitability of martian RSL by measuring in situ the volume of liquid water and its thermodynamic activity.

RSL are highly spatially heterogeneous: they occur at specific sites with dimensions of a few km or less and even within the best sites they cover only ~50% of the surface. Thus the principal mission challenges are both accurate targeting to an RSL site and sampling of an RSL per se. DartDrop addresses these challenges by (1) guided parawing flight to an RSL site and (2) release of multiple small penetrators: 6 darts yield a 98% probability of landing on at least one RSL.

The entry and descent follows the MarsDrop architecture. Deep Space 2 heritage entry vehicles achieve subsonic deceleration at 5-10 km altitude. The parawing can be autonomously navigated to the nearest RSL site up to 10s of km distant. The descent vehicle releases 6 Darts (17x4 cm) at ~100 m altitude. Drogue chutes provide aerodynamic stability and orbital-imaging targets. Measurements begin immediately after landing and continue at timed intervals for a 6-hr threshold, 30-hr baseline, or 42-hr



extended mission. Data are independently uplinked at UHF to an orbiter.

The Darts use Phoenix-heritage sensors to measure subsurface and air temperature (T), atmospheric relative humidity (RH), and subsurface electrical conductivity (EC). The volume of water and its solute concentration can be assessed jointly from T and EC: assessment of habitability (but not life detection) can be made solely from these quantities. Category IVc planetary protection can be easily implemented on these small spacecraft.

SESS05-05: AEOLUS - A MISSION TO STUDY THE THERMAL AND WIND ENVIRONMENT OF MARS

Dr. Anthony Colaprete¹, Dr. Amanda Cook¹, Mr. David Mauro¹, Dr. Melinda Kahre¹, Dr. Robert Haberle¹

¹Nasa Ames Research Center, Mountain View, United States

Aeolus is a small satellite mission to observe surface and atmospheric forcing and general circulation of Mars, by measuring surface energy balance, atmospheric temperatures, aerosols and clouds, and winds. Critically, Aeolus will make these measurements at all local times of day, providing information on both seasonal and diurnal variability. To date, direct measurements of Martian wind speeds have only been possible at the surface, only during daylight hours, and over small areas limited by rover traverse capabilities. From orbit, thermal measurements (e.g., estimates from assumed geostrophic balance) as well as images of dust storms and dune migration have provided inputs to derive current data sets on Martian winds. However, Mars General Circulation models demonstrate that wind speeds derived from these indirect measurements may be in error by 50 to 100%. For this reason, direct wind velocity measurements have been deemed "High Priority" by MEPAG (Mars Exploration Program Analysis Group); measuring wind speeds and corresponding thermal data is vital to understanding the climate of Mars.

Aeolus will carry four Spatial Heterodyne Spectrometers (SHS), coupled to two orthogonal viewing telescopes. These high-resolution near-infrared spectrometers will measure CO₂ (daytime absorption) and O₂ (day and night emission) lines in the Martian atmosphere. Doppler shifts in these lines can be measured during Martian day and night, resolving wind speeds down to ~5 m/s. Orthogonal views allow the spectrometers to capture wind vectors over all observation locations. Aeolus will also carry the atmospheric limb-viewing Thermal Limb Sounder (TLS) to measure atmospheric temperatures, water ice clouds, and dust abundances across all altitudes where winds are measured. Finally, the Surface Radiometric Sensor Package (SuRSeP), a nadir viewing radiometer, will measure the total reflected solar and emitted thermal radiance, surface temperature, and water cloud and dust total column abundances. The combined spectral and thermal measurements will provide a new understanding of the global energy balance, dust transport processes, and climate cycles in the Martian atmosphere. Aeolus will consist of a single satellite in a near-polar orbit, allowing it to pass over all local times, with the baseline mission observing all seasons of an entire Martian year (two Earth years).

Aeolus was one of two Martian smallsat concepts selected for study through the Planetary Science Deep Space SmallSat Studies program. This talk will provide an overview of the mission, including science rationale, instruments, spacecraft, and mission operations concept.

SESS05-06: BENEFITS OFFERED BY A NETWORK OF CUBESAT-CLASS ROVERS FOR PLANETARY CAVE EXPLORATION

Dr. Abigail Fraeman¹, E. Jay Wyatt¹, Joseph Lazio¹, Julie Castillo-Rogez¹, Steven Chien¹, Sebastian Herzig¹, Jay Gao¹, Farrah Alibay¹, Konstantin Belov¹, Douglas Ellison¹, Hongman Kim¹, Nathan Guy¹, Martina Troesch¹, William Walsh¹

¹Jet Propulsion Laboratory, Pasadena, United States

The past decade has seen increasing interest in planetary cave exploration. Dozens of skylights have been found on Mars by the Mars Reconnaissance Orbiter and hundreds on the Moon from the Lunar Reconnaissance Orbiter. Pictures of lunar caves display stratification that provide an in-place record of the Moon's magmatic evolutionary history. Martian caves may represent astrobiological sites that have offered shelters for past and possibly current life, and could serve as volatile traps that record Mars' climate evolution. Caves on both the Moon and Mars are exciting prospective habitats for future crewed missions because they likely offer radiation protection and a stable temperature environment. Robotic planetary cave exploration would be challenging for a multitude of reasons. Uncertainty in the target terrain requires robust mobility systems. Communication between assets within a cave and to the surface would be difficult due to the chaotic signal propagation. The absence of sunlight requires all power needed for instrument operations, data processing and communication to be brought into the cave.

We focus on utilizing a variety of assets to mitigate challenges related to communication and instrument operations while optimizing data acquisition and science data retrieval via an organized network. We developed a set of science objectives and requirements for a reconnaissance mission concept to a Martian cave focused on mapping the cave geometry, composition, and measuring the temporal and spatial variability of cave environmental conditions (temperature, radiation, and humidity). The proposed payload leverages recent or emerging miniaturized instruments developed for CubeSat-class deep space missions. The mild radiation and thermal environment expected in caves justifies the use of CubeSat-class instruments while the multiple assets provide redundancy.

We studied heterogeneous architectures where responsibilities (science, telecom) are distributed among assets. The conceptual DuAxel rover is assumed to be the carrier and telecom relay to the Martian orbiters and may also offer a computing node to support the smaller assets' semi-autonomous navigation inside the cave. Our study includes trade-offs between potential power sources, homogeneity and heterogeneity of the assets, as well as distribution of science instruments to optimize cost and achieved benefit.

Predecisional information for planning and discussion only.

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SESS05-07: SPACECRAFT PENETRATOR FOR INCREASING KNOWLEDGE OF NEOS (SPIKE)

Erik Asphaug¹, John Baker², Mathieu Choukroun², Roberto Furfaro³, Paul Sava⁴, Dan Scheeres⁵, Steve Schwartz¹, Tim Swindle³, Jekan Thangavelautham¹
¹Arizona State University, Tempe, United States, ²Jet Propulsion Laboratory, Pasadena, ³University of Arizona, Tucson, ⁴Colorado School of Mines, Golden, ⁵University of Colorado, Boulder

Hundred-meter asteroids represent a unique niche in interplanetary exploration: they are common and important (to science, hazards and resources) and a spacecraft can land on them in free-fall (escape velocity 10 cm/s). The advent of ESPA-class Solar Electric Propulsion technology allows us to design a low cost, robust strategy for multi-NEO landers that deploy penetrators at the end of a meters-long boom, to conduct subsurface volatile and organics determination and seismology. The SEP bus is kept at safe distance from the surface, landing in an inverted pendulum configuration atop the science payload. In the very low gravity environment (<0.1 cm/s²) the spacecraft arrives and departs using SEP, requiring only small thrusters for ACS; a slight mechanical push allows liftoff for a series of landings, and a journey to a second and possibly third NEO.

SESS05-08: INTREPID: A FLEET OF HIGHLY AUTONOMOUS SMALLSAT NEAR EARTH ASTEROID (NEA) EXPLORERS – MISSION CONCEPT AND SCIENCE INSTRUMENT DEVELOPMENT

Ms. Carol Raymond¹, Ms. Bethany Ehlmann^{1,2}, Mr. Steve Chesley¹, **Dr. Jordana Blakesberg**¹
¹Jet Propulsion Laboratory, California, United States, ²California Institute of Technology, Division of Geological and Planetary Sciences

The Intrepid mission concept calls for a phased deployment of a fleet of small highly autonomous rendezvous spacecraft designed to characterize the evolution, structure and composition of dozens of Near-Earth Asteroids (NEAs). The science goals of the mission concept are threefold: (1) to understand the evolutionary processes that govern asteroid physical, chemical and dynamical histories and relate these results to solar system origins and evolution; (2) to facilitate impactor deflection scenarios for planetary defense by statistically characterizing relevant asteroid physical properties; (3) to quantify the presence and extractability of potentially useful resources on a large sample of asteroids. To achieve these cross-disciplinary goals, the baseline architecture includes the ability to carry instruments designed to identify and characterize volatile-rich targets, focusing on several key questions: what is the total quantity of water contained in each object? How is the water incorporated (ice vs. hydrated silicates)? Are organics present? What types? What is the physical structure of the objects (macroporosity; layering, water ice lenses)? How would the object respond to impact/deflection? A multiple-modular-instrument architecture is needed to address all of these questions. We have begun development of one such instrument that is a cornerstone of the proposed Intrepid payload: a miniature infrared point spectrometer covering both shortwave infrared (SWIR) and mid-infrared (MIR) spectral bands in a compact form-factor, (targeting a 2U volume), making it both relevant to Intrepid and implementable on a Cubesat. Scientifically, the combination of SWIR and MIR measurements into a single integrated instrument would enable robust compositional interpretations from a single dataset combining both solar reflectance and thermal emission spectroscopy. These measurements would be crucial to determining how much water is present in each object, as well as how it is incorporated (e.g. ice vs. hydrated silicate minerals). Other crucial instrument modules include high-resolution cameras, radar sounders, and projectiles that could

interact with the target asteroid. We will present both an overview of the Intrepid mission concept and the infrared spectrometer as a key payload element.

This work has been conducted at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA)

SESS05-09: CHARGE: A SMALL SATELLITE MISSION CONCEPT TO EXPLORE CRITICAL, BUT CHALLENGING REGIONS AT JUPITER

Dr. George Clark¹, Dr. Smith H.T.¹, Dr. Ian Cohen¹, Larry Frank¹, Dr. Chris Paranicas¹, Dr. Peter Kollmann¹, Dr. George Ho¹, Dr. Fran Bagenal², Dr. Peter Delamere³
¹Johns Hopkins University Applied Physics Lab, Laurel, USA, ²University of Colorado, Boulder Laboratory for Atmospheric and Space Science, Boulder, USA, ³University of Alaska Fairbanks, Fairbanks, USA

CHARGE is a small satellite mission concept to explore the relative contribution to the neutral and plasma tori around Europa from its surface, atmospheric and possible geyser interactions as opposed to other Jovian sources. To accomplish this task, there are several key science and measurement objectives that make it possible to distinguish the tori being created from Europa versus Io, the two possible sources being debated in the community. The scientific payload consists of a suite of instruments to diagnose the thermal and suprathermal electron and ion composition and charge states between Io and Europa. This mission will provide the first ever measurements of the detailed ion major and minor species and charge state information in the region between Io and Europa. The high radiation environment in this region had proven too risky for larger, more expensive missions, however it is extremely well suited for lower cost, focused missions. These data are expected to have two additional major impacts on our current knowledge: 1) the data will help us understand the material Io and Europa are pumping into the Jovian system and 2) the data will constrain and confirm or reject the physics driving the chemistry models used to understand the role of Europa and Io in the Jovian system.

NASA has asked the planetary community to examine small satellites with high impact science objectives that may be a part of the future for planetary science. Such a hypothetical program may explore ~\$100M concepts to deep space via a ride share (i.e., piggyback on Europa Clipper) or standalone launches. CHARGE is well suited for such a program and can be implemented on a future ride share to the Jovian system with little burden to the host spacecraft. In fact, it would be best to ride along with a planned mission to Jupiter, such that it can provide important and complimentary measurements in a region that is not planned for investigation by current and future spacecraft.

In this presentation, we discuss the high impact science objectives of the CHARGE mission as well as current technologies that enable small satellites to deep space. We show that these missions are feasible and that future of deep space exploration with smaller satellites offers rich and diverse scientific opportunities.



SESS05-10: JUPITER MAGNETOSPHERIC BOUNDARY EXPLORER (JUMPER)

Dr. Robert W. Ebert¹, Dr. Frédéric Allegrini^{1,2}, Dr. Fran Bagenal³, Mr. Chip Beebe¹, Dr. Mihir Desai^{1,2}, Mr. Don George¹, Mr. John Hanley¹, Dr. Neil Murphy⁴, Mr. Aron Wolf⁴

¹Southwest Research Institute, San Antonio, United States, ²University of Texas at San Antonio, San Antonio, United States, ³University of Colorado at Boulder, Boulder, United States, ⁴Jet Propulsion Laboratory, Pasadena, United States

The JUper Magnetospheric boundary Explorer, JUMPER, is a Jupiter orbiting SmallSat mission concept to explore the planet's magnetospheric boundaries and image its energetic neutral atom (ENA) emissions. It has been selected for further study through NASA's Planetary Science Deep Space SmallSat Studies (PSDS3) program.

JUMPER's science objectives focus on how the solar wind interacts with Jupiter's magnetosphere and the contribution of ENAs to mass loss from the jovian space environment. These objectives will be met with a science payload consisting of two ion sensors, a magnetometer, and an ENA imager. Measurements from these instruments will complement simultaneous observations of Jupiter's magnetosphere and aurora from a primary spacecraft (e.g. Europa Clipper, Jupiter Icy moons Explorer, Io Observer, etc.) and/or any Earth based-observatories, providing a multi-point platform from which to study the dynamics of this system.

JUMPER's science objectives drive several top-level requirements on mission design. The most important is an orbit that includes several passes through Jupiter's bow shock and magnetopause on the dayside of Jupiter. Mission design is also constrained by the necessity to ride share on a primary vehicle, at least until after Jupiter orbit insertion.

The JUMPER spacecraft design derives heritage from SmallSats developed for the Southwest Research Institute (SwRI)-led Cyclone Global Navigation Satellite System (CYGNSS) mission. It consists of an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) compatible frame supporting four double-deployed solar array panels, ESPA ring interconnections, four science instruments, and a radiation vault to house the spacecraft avionics and payload subsystem electronics. JUMPER will use its peri-jove periods to transmit data to the primary spacecraft and execute ranging activities. It will de-orbit into Jupiter at end of mission.

In this presentation, we will provide further details of the JUMPER mission concept and report on progress of the mission concept study.

SESS05-11: JOVIAN ORBITERS LIKE THEMIS (JOLT): A MULTI-SPACECRAFT MISSION CONCEPT TO EXPLORE JUPITER'S DYNAMIC MAGNETOSPHERE

Dr. Frank Crary¹, Dr. Peter Delamere², Dr. Marissa Vogt³, Dr. Abigail Rymer⁴, Dr. Chris Arridge⁵

¹University of Colorado, Boulder, United States, ²University of Alaska, Fairbanks, United States, ³Boston University, Boston, United States, ⁴Johns Hopkins University Applied Physics Laboratory, Laurel, United States, ⁵University of Lancaster, Lancaster, United Kingdom

The magnetosphere of Jupiter is driven by plasma produced by Jupiter's moon, Io. The ionization and transport of this plasma from Io to approximately 10 jovian radii have been studied by the Voyager and Galileo missions. But what happens to this plasma beyond 10 jovian radii is not well understood. Ultimately, this plasma flows down the planet's magnetosphere and, in the process, drives magnetospheric dynamics

leading to, among other things, the energization of radiation belt particles and the generation of Jupiter's aurora.

Numerical models and analogies to the Earth's magnetosphere suggested that this process would involve the occasional release of large-scale "plasmoids." Actual observations by the New Horizon spacecraft, during its Jupiter flyby, are completely inconsistent with this picture. In contrast, and suggested by Cassini measurements of Saturn's magnetosphere, recent work has suggested the process may be more of a continuous "drizzle."

Similar problems have been successfully investigated in the Earth's magnetosphere. The Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission studied the coupling of plasma flows and currents from the deep magnetotail to the Earth. The same approach can revolutionize our understanding of plasma transport and dynamics in the jovian magnetosphere. THEMIS used a set of five small spacecraft (75 kg dry mass) in eccentric, resonant orbits. Periodically, they would all be at apoapsis and in a line extending down the Earth's magnetotail. In this presentation, we describe a Discovery-class mission to Jupiter involving four, 150-kg (dry mass) spacecraft.

SESS05-12: EUROPA SURFACE AND PLUME SAMPLING CUBESAT EXPLORER

Prof. Jekan Thanga¹, Richard Foster-Turner³, Andrew Hunt³, Prof. Alyssa Rhoden¹, Dr. Drew Jones⁴

¹Arizona State University, Tempe, United States, ²University of Alabama, Huntsville, Huntsville, United States, ³Atout Process, Bridport, United Kingdom, ⁴Jet Propulsion Laboratory, California Institute of Technology, Pasadena, United States

Jupiter's moon Europa is the target of NASA's planned Europa Multi-flyby Mission. The mission hopes to provide the most detailed view yet of the surface and subsurface of Europa and answer some fundamental questions, including whether Europa has a liquid-water ocean beneath a thick ice shelf, and if these conditions may harbor life. It is envisioned the multiple flyby mission would be only the first in a series of missions that could culminate into a surface landing mission. A CubeSat could significantly complement the capabilities of the multiple-flyby spacecraft. It could perform high-risk, high-payoff science missions at low altitudes. A CubeSat could provide unique science data that could not be obtained by the mothership by doing a low-altitude flyby, plume sampling and impact mission. In addition, a CubeSat could perform landing site reconnaissance in preparation for a future surface lander mission. Three factors make a CubeSat concept challenging, including the high radiation in the vicinity of Europa, the low solar insolation of 50 W/m² and extremely low temperatures of -230 °C. Coupled with these challenges, Europa lacks an atmosphere sufficient for aero-braking. Despite these challenges, there are gaming changing opportunities from exploiting the miniaturization of electronics and sensors and actuators to build a miniature spacecraft intended to perform high-risk, high-reward science.

Our concept is focused on having 6U or 12U CubeSat separate from the mothership, 10 hours before a close flyby of Europa lasting 20 minutes. The CubeSat would use its onboard propulsion to attain altitudes of 3 to 12 km above the moon's surface travelling at 4-5 km/s. The CubeSat would travel along a cycloid surface fracture and pass through a potential plume. The onboard plume sampler would use a new class of tomography instrument to measure accumulated water content. The instrument would be able to provide measurements of the water vapor encountered during the flyby. Using the onboard optical navigation techniques, the CubeSat would navigate along Europa's shadowed surface fractures



to obtain detailed images of nearby features at 0.3 to 2 m/pixel. The notional spacecraft has the capacity to sample for and analyze potential plume samples, and this option could be utilized to get first answers about potential plume content. The mission concept culminates with the CubeSat impacting the Europa surface. The artificial impact plume created would be analyzed by the array of instruments onboard the Europa Mission spacecraft for material composition. Advances in GNC are required to handle the unique lighting, low-temperature and high velocity conditions of the mission concept. Our early feasibility work shows a development pathway towards advancing the requisite technology towards technical feasibility. Further advancement of this technology can lead to a modular standard for deep space mother-daughter space system architectures and for next generation CubeSats to explore the outer solar systems and beyond.

SESS05-13: SNAP: SMALL NEXT-GENERATION ATMOSPHERIC PROBE

Kunio Sayanagi¹, Robert Dillman², Amy Simon³, David Atkinson⁴, Michael Wong⁵, Thomas Spilker⁶, Sarag Saikia⁷, Drew Hope²

¹Hampton University, Hampton, United States, ²NASA Langley Research Center, Hampton, United States, ³NASA Goddard Space Flight Center, Greenbelt, United States, ⁴Jet Propulsion Laboratory, Pasadena, United States, ⁵University of California, Berkeley, Berkeley, United States, ⁶Planetary Mission Architect, Pasadena, United States, ⁷Purdue University, West Lafayette, United States

We present a concept for a small, atmospheric probe that could be flexibly added to future missions that orbit or fly-by a giant planet as a secondary payload, which we call the Small Next-generation Atmospheric Probe (SNAP). SNAP's main scientific objectives are to determine the vertical distribution of clouds and cloud-forming chemical species, thermal stratification, and wind speed as a function of depth. As a case study, we present the advantages, cost and risk of adding SNAP to the future Uranus Orbiter and Probe flagship mission; in combination with the mission's main probe, SNAP would perform atmospheric in-situ measurements at a second location, and thus enable and enhance the scientific objectives recommended by the 2013 Planetary Science Decadal Survey and the 2014 NASA Science Plan to determine atmospheric spatial variabilities.

We envision that the science objectives can be achieved with a 30-kg entry probe ~0.5m in diameter (less than half the size of the Galileo probe) that reaches 5-bar pressure-altitude and returns data to Earth via the carrier spacecraft. As the baseline instruments, the probe will carry an Atmospheric Structure Instrument (ASI) that measures the temperature, pressure and acceleration, a carbon nanotube-based NanoChem atmospheric composition sensor, and an Ultra-Stable Oscillator (USO) to conduct a Doppler Wind Experiment (DWE). While SNAP is applicable to multiple planets, we examine the feasibility, benefits and impacts of adding SNAP to the Uranus Orbiter and Probe flagship mission.

SESS05-14: COMMERCIAL PARTNERSHIPS FOR EXPLORATION: MAKING SMALL LUNAR MISSIONS VIABLE

Dr. Susan Jason¹, **Mr Steve Eisele**⁴, Mr Jonathan Friend¹, Mr Chris Saunders¹, Mr Matthew Cosby², Mr Bernhard Hufenbach³, Dr James Carpenter³, Ms Veronica La Regina³, Mr Alex Da Silva Curriel¹, Professor Martin Sweeting⁵

¹Surrey Satellites, Guildford, United Kingdom, ²Goonhilly Earth Station,

Goonhilly Downs, Helston, United Kingdom, ³European Space Agency, European Space Technology Centre, Noordwijk, Netherlands, ⁴Surrey Satellite Technology US, Englewood, USA, ⁵Surrey Space Centre, University of Surrey, Guildford, United Kingdom

Small satellite and CubeSat technologies have made budget space missions accessible to a wide range of organisations for furthering education, science, outreach, technical and business objectives. Many emerging space nations use this format and over 40 nations have placed CubeSats into orbit. The utility and ambition of small satellites continues to increase and a wide range of Lunar and Interplanetary CubeSat missions are being proposed and developed for flight.

However there are still several barriers for such resource constrained mission including affordable transportation opportunities to these more challenging destinations and communications with Earth.

In this presentation we describe our plans to provide transport to lunar and interplanetary orbits and subsequent data relay services forming 'core infrastructure services' to support Small Satellite and CubeSat exploration missions. The plans are being detailed under a 'Commercial Partnership for Exploration' pilot phase between ESA, SSTL and Goonhilly Earth Station Ltd. Our longer term vision is to provide commercial communications and navigation services to support sustained human presence on the Moon, Mars and beyond.

The Lunar Communications Pathfinder is the first planned mission, comprising a 'Mothership' which delivers customer Small Satellite and CubeSat missions into Lunar Orbit. The Mothership then provides data relay services with Earth via a dedicated ground segment. The subsequent missions in the series focus on development of the exploration services including increased data relay capacity and augmented navigation services.

The missions are financed by ticket pre-sales for the services with a range of incentives for early adopters of the system. There is significant international interest and commitment from industry, space agencies and commercial companies keen to be customers and pioneering partners for this mission and its successors. We will present the current status and next steps towards project implementation and launch in the 2020 timeframe.

SESS05-15: MOON DIVER: A DISCOVERY MISSION CONCEPT FOR THE EXPLORATION OF A LUNAR PIT CRATER USING THE AXEL ROVER

Dr. Laura Kerber¹, Issa Nesnas¹

¹Jet Propulsion Laboratory / Caltech University, Pasadena, United States

The lunar mare basalt deposits serve as natural probes into the lunar interior. Studies of the morphologies, chemistries, and spectral properties of impact-exposed and regolith-mantled surface basalts have yielded major insights into the thermal history and chemical composition of the Moon. Recent images returned by the Kaguya and Lunar Reconnaissance Orbiter missions have revealed the presence of deep mare pits containing meter-scale layer stratigraphy exposed in their walls, providing unprecedented access to in-place mare bedrock stratigraphy. A mission to such an exposure would address numerous top priority lunar science goals laid out in community reviews, the Decadal Survey, and the Lunar Exploration Roadmap. Before now, the desire to send a mission to these targets was tempered by the difficulty of reaching them given the mobility of traditional rovers. The Axel Extreme Terrain Rover, developed by the Jet Propulsion Laboratory in collaboration with Caltech, has the mobility necessary to approach, anchor, and rappel into this type of pit, revolutionizing our capability to access and explore in-place stratigraphy



on the Moon. The Axel rover consists of two wheels connected by a thick axle containing a winch and a tether. Scientific instruments are housed inside the wheel well. Over flat terrains (for example, from the landing site to the investigation area), the Axel rover can traverse like an ordinary rover. Once it approaches a steep section, the Axel rover can set an anchor and rappel down the steep slope by letting out the tether stored inside the axle. Two Axels can be combined to form a "DuAxel". This functionality allows the rover to descend steep to vertical slopes (and ascend them again). The rover can even dangle in free space and continue to let out its tether. The rover can communicate through its cable, alleviating common communication problems facing other cave-exploring robots. The rover can also receive power through its tether, meaning that it could leave a solar panel on the surface and still receive power to explore a dark cave below. The functionality of this rover would allow a mission to examine and characterize lava layers exposed in the wall of a mare pit crater during abseil descent. Mineralogy (provided by the spectrometer), texture (provided by a microimager), and measurements by additional instruments (housed by Axel's 6-8 instrument bays), or on the larger body of the DuAxel, would reveal changes in composition and morphology throughout the section. Axel's onboard cameras could record layer thicknesses and document the presence and characteristics of intervening paleoregolith layers. Once on the floor of the pit, if a subsurface lava tube is discovered, Axel could explore potentially up to 1 km underground. After exploring the pit, the rover could reel itself back up the wall and either continue roving across the surface or rappel down a different side of the pit.

SESS05-16: ROCKSAT: MAPPING THE MOON'S COMPOSITION AT THE 10-M SCALE

Dr. Paul Lucey¹, Dr. G. Jeffrey Taylor¹, Dr. Peter Mougini-Mark¹, Dr. Jeffrey Gillis-Davis¹, Dr. Miguel Nunes¹, Dr. Robert Wright¹, Dr. Scott Richey², Dr. Brittany Wickizer²

¹University Of Hawaii, Honolulu, United States, ²NASA Ames Research Center, Moffatt Field, USA

Rocksat: Mapping the Moon's Composition at the 10-m Scale

Paul G. Lucey, G. Jeffrey Taylor, Pete Mougini-Mark, Jeff Gillis-Davis, Miguel Nunes, Robert Wright, University of Hawaii at Manoa; Scott Richey, Brittany Wickizer, NASA Ames Research Center

RockSat is a single instrument lunar orbiter mission to collect compositional and thermophysical information about the Moon at unprecedented 6-m spatial resolution enabling breakthrough science. The instrument is a thermal infrared hyperspectral imager supported by NASA's Earth Science Instrument Incubator Program and several DoD projects. Currently, basic mineralogy of the Moon is available at 60-m resolution, and near-IR spectroscopy measurements at 100-m resolution, so RockSat provides measurements at 10 times higher linear resolution and 100 times higher resolution in area.

RockSat wavelength coverage at thermal wavelengths covers all major and many minor lunar minerals have distinct signatures, whereas in the near-IR only iron-bearing minerals can be directly detected. Important minor minerals including quartz, phosphates and many feldspars are invisible to near-IR spectroscopy, and their presence is inferred through indirect effects on lunar spectra. At resolutions better than 10-m, the lunar surface is strewn unevenly with boulders that preserve the original compositions. RockSat compositional analysis will concentrate on these boulders.

Using chemical propulsion, the RockSat satellite would be on the order of an ESPA ring class spacecraft of about 180 kg; with electric propulsion the instrument could be accommodated in a 27U cubesat. After orbital insertion, the mission would last about 5 months in an evolving ~50x200

km orbit to take advantage of the full range of lunar thermal conditions presented to the instrument.

RockSat is a small secondary spacecraft that rideshares on a primary mission ranging from an outbound interplanetary trajectory to an arbitrary lunar orbit. This constraint is imposed by the propulsion demands to reach and orbit the Moon from LEO or a GEO-bound trajectory. The RockSat spacecraft will separate from the primary spacecraft and transfer to the required science orbit, nominally 40 x 200 km, with periapsis initially over the equator. The science phase lasts for 4-5 months.

The RockSat science orbit design leverages natural gravitational perturbations to manage altitude and orientation for observations. Final orbit lowering is timed to place the periselene on the night side of the sunset terminator, where it will observe the complete range of lunar longitudes and nearly the same sunlight condition during the first lunation. Natural trends in altitude decay and apsidal precession will result in favorable configuration of altitude and latitude approximately 4 months later as the orbit plane arrives over the day side of the Moon, where the satellite will again observe the complete range of lunar longitudes at close to the same sun angle during the last lunation of the Science Phase. With periapsis altitude below 50 km, the orbit will have natural decay within approximately one year, causing the satellite to impact the lunar surface with no propulsive disposal maneuver required after the conclusion of science operations.

SESS05-17: THE LUNAR COMPASS MISSION CONCEPT: ROVER EXPLORATION OF A MAGNETIC ANOMALY

Dr. David Blewett¹, Dr. Dana Hurley¹, Dr. Brett Denevi¹, Dr. Jeffrey Plescia¹, Dr. Edward Tunstel¹, Dr. Christopher Paranicas¹, Dr. Brian Anderson¹, Dr. George Ho¹, Dr. Jorge Nunez¹, Dr. Haje Korth¹, Dr. Joshua Cahill¹, Dr. Rachel Klima¹, Dr. Benjamin Greenhagen¹, Dr. Lauren Jozwiak¹, Dr. Michael Zimmerman¹, Dr. Sabine Stanley¹, Dr. Charles Hibbitts¹, Dr. Pontus Brandt¹, Dr. Joseph Westlake¹, Dr. Jeffrey Johnson¹
¹Johns Hopkins Applied Physics Lab, Laurel, United States

The Moon does not currently possess a global, internally generated magnetic field, but the lunar crust does contain areas of magnetized rocks ("magnetic anomalies"). The lunar magnetic anomalies present a natural laboratory for at least five major areas in planetary science:

- Planetary magnetism: What is the origin of the magnetized material? Current hypotheses include magnetization imprinted during the recent impact of a cometary coma, basin ejecta magnetized by plasma effects, and a magnetized igneous intrusion. By measuring the strength and structure of the field on the surface, it will be possible to constrain the size and the depth of the magnetic source. A surficial anomaly would support a comet impact origin. A deep source might indicate the presence of a magnetized intrusion or a deposit of magnetized basin ejecta, with important implications for an ancient core dynamo and lunar thermal evolution.
- Space plasma physics: How does the magnetic anomaly interact with the incident plasma to form a standoff region? How important are electric fields? What are the fluxes of the particles that actually reach the surface by energy and species? How does the solar wind/magnetic field/surface interaction change with time of lunar day?
- Lunar geology: What are the nature and origin of the unusual, high-reflectance markings (lunar swirls) that are associated with magnetic anomalies? Are they ancient or recent? Has levitated dust or cometary material modified the surface?



d) Space weathering: Space weathering alters the optical and chemical properties of airless surfaces across the Solar System, and it is important to develop a complete understanding of space weathering on the Moon as a blueprint for weathering of other bodies. A key issue relates to the relative importance of plasma vs. micrometeoroid bombardment and what roles these agents play in modifying the surface. The lunar magnetic anomalies offer some control on one of the key variables, solar wind exposure, because most classes of micrometeoroids will not be affected by the presence of the magnetic field.

e) Lunar water cycle: It is known from orbital data that the high-reflectance parts of swirls exhibit weaker hydroxyl absorptions at 2.82 μm than the background, consistent with a lower flux of solar wind protons reaching the surface or a difference in retention. How does this hydration feature vary on the lunar surface, and with location/magnetic field strength?

An instrument package traversing one of the major magnetic anomalies could help to provide answers to these important questions. We have named our rover mission concept "Lunar Compass". The presentation will review the science case for the mission and discuss the science payload under consideration.

SESS05-18: LUNAR WATER SMALL SATELLITE MISSION CONCEPT

Dr. Charles Hibbitts¹, Brenda Clyde¹, Rachel Klima¹, Joseph Westlake¹, Jessica Sunshine², **David Blewett**¹, Barbara Cohen³, Pontus Brandt¹, Jeff Plescia¹, John Dankanich³, Wes Patterson¹
¹JHU-APL, Laurel, United States, ²University of Maryland, College Park, USA, ³NASA Marshall Space Flight Center, Huntsville, USA

The Lunar Water Assessment, Transport, Evolution, and Resource (WATER) mission is a concept selected for study under the NASA NNN16ZDA001N-PSDS3 Planetary Science Deep Space SmallSat Studies program. The concept is for a deep space small spacecraft lunar orbital mission to conduct Discovery-class science for understanding the water on the Moon by leveraging rideshare launch options, new propulsion technology, miniaturization of instrumentation, and improved communications. Specifically, the concept is for an EELV Secondary Payload Adapter (ESPA)-class mission using solar-electric propulsion to answer questions related to the processes behind the formation, loss, evolution and sequestration of water on the Moon. The associated trade studies will consider orbital requirements, instrument payload, and mission duration. This mission will characterize the volatiles (water ice, other forms of H₂O, and OH) on and within the surface of the Moon. Better understanding volatiles in the inner solar system and specifically the Moon is a high-priority objective in the 2014 NASA Science Plan, the 2013-2022 Decadal Survey.

Low-altitude flyovers of different parts of one of the poles and a distant apolune are required mission attributes to achieve this mission and are enabled with Solar Electric Propulsion (SEP). By entering lunar orbit after delivery to the Moon on a rideshare or independently entering from a geostationary transfer orbit (GTO), SEP will slowly bring the spacecraft to a low-altitude perilune of ~ 10 km and distant apolune of a few thousand kilometers. Previous missions were dramatically limited in their investigation of lunar water by not being able to obtain both a global perspective of the Moon with a wide range of terrains seen at one time at different local times of day, and also by not being able to observe inside the PSRs with the appropriate measurements at the appropriate spatial scales to characterize the water/geologic/temperature dependencies. Thus, a highly eccentric orbit is essential for the science and instrument measurements. One goal of this study is to determine a feasible payload

suite from a plethora of possible instruments. Polar perilune will enable high-spatial-resolution measurements of polar volatiles such as with a neutron spectrometer (NS), either an active IR multispectral imager or a multispectral UV imager to characterize the water in the PSRs, and a low size, weight, and power radar sounder to characterize the subsurface ice. At apolune, global information could be obtained on the formation and loss mechanisms and evolution of OH and H₂O on the illuminated Moon using a Faraday cup to measure the solar-wind proton flux impinging on the surface, a neutral atom imager to understand the reflected portion of the solar wind, and the IR spectral imager in passive mode to investigate the OH and any H₂O formed on the Moons' illuminated surface.

SESS05-19: NANOSWARM: A DISCOVERY CLASS LUNAR MISSION TO STUDY SPACE WEATHERING, THE SOLAR WIND, SURFACE WATER, AND REMANENT MAGNETISM

Prof. Ian Garrick-Bethell¹, Prof. Christopher T Russell², Mr. Steven Warwick³

¹University of California, Santa Cruz, Santa Cruz, United States,
²University of California, Los Angeles, Los Angeles, United States,
³Northrop Grumman, Redondo Beach, United States

NanoSWARM was proposed to the 2015 NASA Discovery program to study space weathering, plasma-field interactions at small scales, lunar surface water, and lunar crustal magnetism. The NanoSWARM concept uses approximately three-dozen 3U cubesats, brought to the Moon in a carrier vehicle built around an ESPA ring (the LCROSS bus). Once in lunar orbit, NanoSWARM cubesats use their own propulsion to establish impact trajectories into the hearts of the Moon's strongest crustal magnetic anomalies. These trajectories permit measurements of fields and particle fluxes down to ~100 m altitude in the last tens of milliseconds of flight. Low altitude measurements of lunar polar neutrons are performed with a different subset of cubesats, providing a high-resolution map of polar hydrogen deposits.

Broadly, mother-daughter architectures, where the "mother" is the carrier vehicle and the "daughters" are a group of smaller satellites, offer a number of benefits. Firstly, they permit diverse and high-risk science orbits, such as those at extremely low altitudes. Secondly, they permit real time monitoring of critical events when the Earth is out of radio range. For NanoSWARM, this is important for providing coverage during daughter spacecraft burns and impact events taking place on the farside. Lastly, mother-daughter architectures have some advantages for facilitating international collaboration: contributed daughter spacecraft can be built around the cubesat standard, which is now known around the world.

One of the most interesting trade studies in this architecture is how much risk to assign the carrier vehicle vs. the cubesat daughters. For example, does the carrier help provide orbit changes for each of the cubesats, including establishing them on impact trajectories? To date, few cubesats have used sophisticated propulsion systems, and no cubesat has been deployed beyond Earth. Significant velocity changes and deep-space orbit determination have not been demonstrated. In the extreme, the carrier vehicle could perform all of the trajectory changes, and leave the cubesats entirely as measurement probes, similar to most Earth orbiting cubesats. This risk accommodation trade requires further study, and should incorporate knowledge gained from upcoming cubesat missions.



SESS05-20: THE LUNAR VOLATILES ORBITER: A SOLAR SYSTEM VOLATILES MISSION

Dr. Paul Lucey¹, Dr. Noah Petro², Dr. Bill Farrell², Dr. Xiaoli Sun², Dr. Erwan Mazarico², Dr. Jim Abshire², Dr. Greg Neumann², Dr. Rob Green³, Dr. Rebecca Greenberg³, Dr. David Cameron³, Dr. Dana Hurley⁴
¹University Of Hawaii, Honolulu, United States, ²Goddard Space Flight Center, Greenbelt, USA, ³Jet Propulsion Laboratory, Pasadena, USA, ⁴JHU Applied Physics Laboratory, Laurel, USA

The Lunar Volatiles Orbiter: A Solar System Volatiles Mission

Paul G. Lucey¹, Noah Petro², Bill Farrell², Xiaoli Sun², Erwan Mazarico², Jim Abshire², Greg Neumann², Rob Green³, Rebecca Greenberg³, David Cameron³, Dana Hurley⁴
¹University of Hawaii, ²Goddard Space Flight Center, ³Jet Propulsion Laboratory, ⁴Applied Physics Laboratory

The Lunar Volatiles Orbiter (LVO) is Discovery-class mission concept in development. This lunar polar orbiting mission which leverages the spacecraft design and operations experiment of the Lunar Reconnaissance Orbiter is aimed at understanding the current state of volatiles on the Moon with an emphasis on current dynamics. The mission will carry both surface and atmospheric composition instruments that will definitely answer questions regarding volatile flows to and from the Moon, and their propagation in the lunar environment. A particular emphasis is to use the Moon as a natural laboratory to understand volatile interactions of all airless bodies.

All planetary bodies are exposed to and interact with the solar wind and continuous infall of meteorites. The surfaces of those without atmospheres are directly exposed to this flow and diverse evidence shows can respond differently to this stimulus. Most of the inferences regarding the influence of exposure to space are indirect and researchers invoke differential response of known inputs to explain often conflicting observations. The Moon offers the opportunity to fully understand the response of an airless body to these inputs, providing insights into the general process of space-surface interaction applicable from Mercury to exoplanets. Despite the wealth of sample and remotely obtained data the response of the lunar surface to the solar wind and mass infall of volatiles is only partly understood. A single mission can provide the linkages necessary to form a coherent understanding of the interaction of the Moon and its volatile rich sources.

LVO plans four instrument to address its science objectives : Spectroscopic Infrared Reflectance LIDAR (SpIRRL), a laser spectrometer developed by Goddard Space Flight Center operating in the 3 micron region; the Lunar Volatiles Imaging Spectrometer (LVIS), an infrared imaging spectrometer operating in the 3 micron region; Ion Mass Spectrometer (IMS), developed by Goddard Space Flight Center aimed at detection of water in the lunar atmosphere; and Gamma-Ray/Neutron Spectrometers (GRNS) by APL for high spatial resolution measurement of the abundance and distribution of hydrogen in the polar regions and other proposed hydrogen-rich regions.

Integration of LVO data will provide a complete understanding of how hydrogen flows through the lunar environment and what are the controls, which directly informs our understanding of such interaction on Mercury, Vesta, Ceres and other airless bodies, including asteroids and exoplanets.

SESS05-21: CUPID'S ARROW: A SMALL SATELLITE TO MEASURE NOBLE GASES IN THE ATMOSPHERE OF VENUS AND TITAN

Dr. Christophe Sotin¹, Dr Guillaume Avice¹, John Baker¹, Dr. Murray Darrach¹, Dr Antony Freeman¹, Pr. Glenn Lightsey², Pr. Bernard Marty³, Dr. Stojan Madzunkov¹
¹Jet Propulsion Laboratory, California Institute Of Technology, Pasadena, United States, ²Georgia Institute of Technology, Atlanta, United States, ³CNRS and Univeriste de Lorraine, Nancy, France

One major objective in comparative planetology is to understand why Venus and Earth, two sister planets, have evolved so differently. Noble gases are inert elements that are ideal tracers of processes that have shaped terrestrial planets such as the original supply of volatiles from the solar nebula, the delivery of volatiles by asteroids and comets, the escape rate of planetary atmospheres, the degassing of the interior, and its timing in the planet's history. A major observational missing link in our understanding of Venus' evolution is the elementary and isotopic patterns of noble gases and stable isotopes in its atmosphere, which remain poorly known. For example, Venus Xe inventory is unknown, with a reported upper limit of 4 ppb. On Earth, the nine non-radiogenic isotopes of atmospheric Xe are strongly mass-dependently fractionated. Furthermore atmospheric Xe is depleted by almost 20x compared to a meteoritic Xe/Kr ratio. Despite its elevated mass, most of the terrestrial Xe may thus have escaped. One model to explain this paradox includes major atmospheric blow-off due to stronger solar EUV radiation in the past or a variant where the mechanism is driven by Earth's moon-forming impact followed by preferential replenishment of Kr through degassing. Cupid's Arrow (CA) measurements of the Venus Xe isotopic ratios would test these models. The other noble gases (He, Ar, Ne, Kr) also provide strong constraints on the evolution processes. Such measurements were rated number 1 investigation of objective A (How did the atmosphere of Venus form and evolve?) of goal I (Understand atmospheric formation, evolution, and climate history on Venus) of the VEXAG "Goals-Objectives-Investigation for Venus Exploration" published in 2014. Such measurements in Titan's atmosphere would provide similar critical information.

Cupid's Arrow is a mission concept that would measure the noble gases using state of the art mass spectrometer miniaturized to fit within a small satellite. The Cupid's Arrow Smallsat probe would skim through the atmosphere of Venus, at a closest approach altitude comfortably below the homopause. A compact quadrupole ion trap mass spectrometer (QITMS) developed at JPL over the last decade for high precision noble gas measurements and flight applications would be employed in the CA investigation. A sample obtained below the homopause would be "well mixed" for the noble gas species and a true probe of their fractional abundances in the Venus atmosphere. The CA instrument would obtain a sample of the ram enhanced Venus atmosphere in a small accommodation chamber. Then the Venus major constituent species (e.g. CO₂, N₂) would be removed from the sample by a small ion/getter pump. The resultant sample, with enriched noble gas partial pressures, would be then admitted into the QITMS. Data would be returned either directly to Earth or to a mother spacecraft. The small satellite development would leverage upon the JPL INSPIRE cubesat and other cubesats being developed at JPL.



SESS05-22: PLANETARY AERONOMY AND ATMOSPHERIC ESCAPE FROM SMALLSAT CONSTELLATIONS

Dr. Robert Lillis¹, Dr. Andrew Poppe¹, Dr. Jeffrey Parker²,
Dr. Jordi Suig-Puari³, Dr. Christopher Russell⁴, Dr. Shannon Curry¹,
Dr. Janet Luhmann¹, Dr. David Brain⁵, Dr. Davin Larson¹

¹University Of California Berkeley, Berkeley, United States,
²Advanced Space, Boulder, United States, ³Tyvak Inc, Irvine, United States,
⁴University of California Los Angeles, Los Angeles, United States,
⁵University of Colorado, Boulder, United States

The structure, variability, and dynamics of planetary upper atmospheres and plasma environments are a central research topic in planetary science; the range and interplay of neutral and plasma processes is unique for each planet. In addition, atmospheric escape originates from these complex environments and drives atmospheric evolution, particularly important for understanding the history of Venus, Mars, and Titan particularly. Observations by several spacecraft (e.g. Cassini, Pioneer Venus Orbiter, Venus Express, Mars Express, MAVEN) have greatly improved our understanding of these enigmatic environments. However, these missions have been fundamentally limited by a single platform. For example MAVEN, the only dedicated planetary aeronomy mission, is limited in three major ways: a) spatial and temporal variations in atmospheric escape fluxes cannot be distinguished from one another, b) responses of escape fluxes to changing solar wind conditions (typically ~1 minute) can only be measured with a time-lag of an hour or more (if at all) and c) global escape rate variability in response to space weather "storms", much more common and intense in the early solar system, must be estimated (poorly) from a single orbit track.

Our understanding of plasma motion in the terrestrial magnetosphere previously suffered from many of the same limitations and ambiguities. In the Heliophysics Division, multi-spacecraft missions such as Cluster II (2000), THEMIS (2006), the Van Allen Probes (2012), and MMS (2015), along with constant monitoring of the upstream solar conditions from missions such as Wind (1994) and ACE (1997), have revolutionized our understanding of the causes, patterns and variability of a wide array of magnetospheric and ionospheric phenomena, including magnetic reconnection, aurora, and terrestrial atmospheric escape. In a similar fashion for Mars, Venus and Titan, we will only be able to understand the spatial and temporal variability of ion and neutral escape, the underlying physics of such processes, and ultimately, their importance to climate evolution with multiple spacecraft and a simultaneous solar wind monitor.

We will present a smallsat constellation concept with a flexible science payload of miniaturized in situ plasma and magnetic field sensors along with remote sensing UV/visible instrumentation to achieve this needed breakthrough in understanding. We will present complete mission architectures, including < 2.5 year trajectories to Venus and Mars, optimized orbits to characterize atmospheric ion and neutral escape, and a smallsat bus with propulsion/power/attitude/communication systems necessary to enable mission success.

SESS05-23: LAPLACE – A COMPREHENSIVE EXPERIMENTAL PROTOPLANETARY DUST GROWTH SIMULATION UNDER LONG-DURATION MICROGRAVITY CONDITIONS

Prof. Jürgen Blum¹, Dr. Rainer Schröpfer¹, Ingo von Borstel¹,
Dr. Julie Brisset², **Prof. Joshua Colwell**², Dr. Thomas Driebe³,
Dr. Pascal Heintzmann³, Dr. Andrei Vedernikov⁴, Dr. Daniyar Balapanov⁴
¹Institut für Geophysik und extraterrestrische Physik, TU Braunschweig,

Braunschweig, Germany, ²Florida Space Institute and Center for Microgravity Research, University of Central Florida, Orlando, USA, ³German Aerospace Center (DLR), Bonn, Germany, ⁴Microgravity Research Center, Université Libre de Bruxelles, Brussels, Belgium

Laplace is a planetary mission in low-Earth orbit to carry out a microgravity experiment to simulate the complete first step of the growth of dust in young planetary systems, from initially (sub-) micrometer-sized dust grains to cm-sized agglomerates. From modeling protoplanetary disks, the birth places of planets, it is known that the freshly-condensed dust particles initially collide with each other at very low velocities (1 mm/s). Earlier work has shown that these ultra-low-velocity collisions lead to the formation of fractal aggregates. As the aggregates grow, their mutual collision velocities increase until the aggregates are compacted at velocities 1 cm/s, leaving the simple-to-describe hit-and-stick regime. No experimental work on the evolution of fractal dimensions, aggregate mass-frequency distribution and sticking probabilities has been performed so far.

Onboard the Laplace satellite, we will disperse a dust cloud and manipulate it under long-duration microgravity conditions such that all stages from ultra-low-velocity hit-and-stick collisions to high-velocity compact growth or even bouncing (if it occurs) can be studied. With specially-arranged micro-Peltier elements, which result in locally and temporally varying gas temperatures that cause thermophoretic forces on the dust particles, the dust cloud can be moved or squeezed and collisions among dust aggregates can be generated. Starting with a number density of $10^6 \mu\text{m}$ -sized dust particles per cm^3 in a rarefied-gas environment of ~100 Pa pressure and an active volume of a few cm^3 , we expect to produce by collisional coagulation aggregates consisting of almost all available dust monomers ($\sim 10^6$ - 10^7) within ~1000 s into a single aggregate with 1-10 mm diameter. Due to the extended parameter range (dust material, monomer-grain size and size distribution, velocity-size relation in the non-Brownian motion regime), at least 50-100 individual experiment runs have to be performed. At all stages during an experimental run, the size, morphology and velocity of the dust aggregates present will be measured through scanning long-distance microscopy.

All major experimental components (dust handling and dispersion, gas and vacuum system, long-distance microscopy, dust-cloud trapping and manipulation) have been developed and successfully tested in drop-tower and parabolic flights. Automated dust-cloud control (levitation, scanning, agglomerate centering, trap centering) is under development. Laplace can fly in a 24U configuration as an independent satellite, or in a smaller configuration (~12U) as a hosted payload on the ISS or other platform.



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