Report on

The IAA 12th Low-Cost Planetary Missions Conference

Pasadena, CA, August 15-17, 2017

The 12th Low-Cost Planetary Missions Conference (LCPM-12) was held in the Hameetman Auditorium of the Cahill Center at the California Institute of Technology, August 15-17, 2017. This was the most recent in a series of conferences on low-cost planetary missions, dating back to 1994, and organized under the auspices of the International Academy of Astronautics (see Appendix A for a list of prior dates and locations). The three-day conference had 113 registered attendees from eight countries (United States, France, Japan, Israel, United Kingdom, Peru, Germany, Mexico), and consisted of 68 oral presentations spanning three days, a three-hour poster and networking reception, and a conference banquet.

The focus of LCPM-12, as with prior instances of the conference, was on small and/or low-cost planetary missions, defined to be on the scale of the NASA Discovery/ESA Cosmic Vision Small (S) Class and smaller, including SmallSats and CubeSats. The conference was intended to be an opportunity for scientists, technologists, engineers and project and agency managers to exchange ideas and information to enhance the viability and science return of low-cost robotic missions.

Several VIPs were in attendance at the conference, including Dr. Jakob van Zyl, Director of the Jet Propulsion Laboratory Solar System Exploration Directorate, who provided opening remarks, and David Schurr, Deputy Director of the NASA Science Mission Directorate, Pierre Bousquet, Head of Planetary Science at CNES, and Professor Hitoshi Kuninaka of JAXA-ISAS, Project Manager of the Hayabusa2 Asteroid Explorer mission, who reported on their respective national low-cost exploration programs.

The conference was spllit into six sessions, ranging from programmatic and institutional issues, to current, forthcoming and more distant low-cost mission concepts. The conference was conducted fully in sequential plenary sessions, augmented by one evening poster session. These sessions included:

- <u>Agency Programs and Plans for Low-Cost Planetary Missions</u>: This session consisted of talks by representatives of three national space agencies, NASA, CNES and ISAS/JAXA, who reported on their respective agency low-cost programs. Of particular interest to the audience was the NASA presentation on funded CubeSat/SmallSat concept studies funded under the Planetary Science Deep Space SmallSat Study (PSDS3) program, and information about the forthcoming SIMPLEx-2 program for formulation and development of small spacecraft science investigations. These programs are actively funding development of small, low-cost missions, and presently make up the bulk of NASA's activity in these areas for planetary science. The report from CNES highlighted the many instrument activities being pursued in France, including instruments on the Mars Science Laboratory and Rosetta missions. Recently, a joint agreement was made between CNES and TeamIndus, a private Indian aerospace corporation, to provide cameras for TeamIndus' proposed lunar rover, building off their extensive experience in miniaturized CCDs from the Rosetta, Phobos-Grunt and MSL missions. ISAS/JAXA is developing a technology demonstration lunar lander, SLIM (Smart Lander for Investigating the Moon), in order to show capabilities of pinpoint soft landings on the lunar surface. The sophisticated lander has autonomous obstacle detection, a robust guidance system and small science payload. It is anticipated to be the precursor of full-scale lunar or other planetary missions that require soft landing, and is under active development for launch and landing in 2018.

- <u>Low-Cost Mission Infrastructure and Considerations</u>: In this session, representatives from three of NASA's planetary assessment groups (MEPAG, OPAG and VEXAG) provided reports on the utility and role of small spacecraft to their respective planetary bodies (Mars, outer planets and Venus, respectively). While the value of small spacecraft for Mars and Venus exploration is well understood, the value of small spacecraft for exploration of Ocean Worlds and the outer planets is less clear. Conference participants engaged in a lively discussion about different ways to explore more distant worlds in a 'low cost' framework. Clearly, Discovery-class missions (such as New Horizons) can perform substantial science for a relatively low cost. PSDS3-funded studies will flesh out small satellite concepts for ride-along with future large spacecraft. One additional area in which the outer planets can leverage low-cost missions is in the development of CubeSat technology to reduce SWaP (size, weight and power) of critical spacecraft components, enabling exploration that was previously unachievable.

  Additional talks were given on the SPICE information system for determining spacecraft geometry, and on the process of archiving science data on the NASA Planetary Data System (PDS). These items, available to both large and small spacecraft, are necessary components to achieving science goals of low-cost missions, and making the data available to the wider community. Ancillary data on the time and observation geometry of a mission using SPICE is critical for mission design, observation planning and development of science data analysis software, yet there are no NASA mandates on the production of such ancillary data. Under low cost mission constraints, production of ancillary data may be assigned secondary importance, yet the audience was encouraged to give it heed so as to maximize the ultimate value of the retrieved science data. A presentation about the PDS highlighted the need to implement an archiving infrastructure for smaller missions. Archiving of data from US missions into the PDS is required, yet the process is not straightforward—there are restrictions and specific formats for data, which must be met by even the smallest missions. Sufficient resources must be retained to perform these tasks.

  These presentations served as an important reminder that certain obligations need to be met by even low cost (CubeSat, SmallSat missions). While technology can be miniaturized to fit within SWaP constraints, and capabilities can be limited to fit within cost caps, there are certain irreducible costs that go along with even the smallest missions that must be acknowledged and budgeted.

- Active Missions and Missions Currently Under Development for Launch in the Near Future: A number of small and low-cost missions are currently active, or scheduled for launch in the near future from several nations. Several missions in the JAXA portfolio were discussed, including Hayabusa2 and the MINERVA-II asteroid explorers, and the DESTINY+ technology demonstrator. The Hayabusa2 mission will arrive at asteroid 162173 Ryugu in July of 2018, depart in late 2019 and return to Earth in late 2020, bringing with it a pristine sample of asteroid material. Other low-cost missions of various scales, and in various stages of development, were presented. Some, like EQUULEUS, NEA Scout and LunaH-Map, are CubeSat missions ready for near-term launch on EM-1 (Exploration Mission 1), the unmanned first flight of NASA's SLS system. Others, like AIDA/DART (Asteroid Impact and Deflection Assessment/Double Asteroid Redirection Test) are technology demonstrations for deep space operation, and yet others, like Q-PACE are Earth-orbiting CubeSat experiments. Q_PACE is designed to explore the properties of low velocity particle collisions in microgravity to understand protoplanetary growth from pebble-sized (cm-scale) objects to boulder-sized (m-scale), and the development of planetary rings. Highlighting the creativity with which missions are being designed under the low-cost mantle, the Q-PACE design is built on a commercial GoPro camera and Raspberry Pi controller for its operations.

  A presentation by Blue Skies Space, Ltd. on the Twinkle satellite, introduced the community to a novel approach to a commercially operated satellite for performing science investigations. In the case of Twinkle, this includes visible and IR spectroscopic measurements (0.4-4.5 μm) of the chemical composition of exoplanetary atmospheres and solar system bodies such as asteroids. Observation time on the Twinkle satellite may be purchased, commercially, by individuals, institutions, or even space programs. Data is acquired, downlinked and delivered to the client per their request. There was interest among the audience about the logistics and financials associated with this novel approach, which has the potential to open up space science to a wider global audience. Initial costs, as presented, seemed on par with costs for existing techniques (e.g. ground-based and aerial telescopes). Anticipated launch is by the end of 2020.

- Science Instruments Enabling the Next Generation of Low-Cost Planetary Exploration: This session focused on two distinct areas of science instrumentation, and development for future low-cost missions—imaging instruments of various types from the UV to NIR, and non-imaging instruments, largely focusing on electromagnetic instrumentation and radio science. Within this section, instruments are, in some instances, incorporated into notional payloads for forthcoming CubeSat and/or SmallSat missions. Several, however, are still seeking a ride into space.

A presentation on low-cost advances in studying planetary atmospheres and interior structures using only precision radios on small spacecraft demonstrated the possibilities of using multiple satellites, in a GRAIL-like system, to infer the interior structure of planets, and tidal effects. Similar systems have been proposed in the past to calculate atmospheric temperature and density using only radio signals between co-orbiting spacecraft. In more traditional architectures (i.e. not low-cost), radio science experiments are often done opportunistically, at little to no added cost to the mission. For example, by sending a signal direct-to-Earth as a spacecraft passes behind a planet, the signal can be distorted by passage through the intervening atmosphere. The signal can be inverted to extract physical properties of the atmosphere. Incremental additions to this basic concept, such as inclusion of an ultra-stable oscillator (USO) or a dedicated Ka-band transponder can greatly improve the ability of such spacecraft to perform radio science. Ongoing development of USOs for small spacecraft, and software-based transponders that can fit in CubeSat architectures will allow science-quality radio communication between multiple low-cost small spacecraft or other configurations including a 'mother-daughter' formation, and increase the science return of these low-cost missions.

Several imaging instrument designs were presented, highlighting advances in imaging technology. These instruments not only advance the state of the art over what is currently operating in space, but do so in much smaller form factors that can fly as CubeSat payloads. As an example, the Advanced Multispectral Infrared Microimager (AMIM), designed out of the Johns Hopkins University Applied Physics Laboratory is a microscopic imaging 'hand lens' in the style of the MSL MAHLI imager, MER Microscopic Imager or the Mars 2020 SHERLOC microscopic imager, but in a ~2U form factor with broad spectral range, a wide range of spectral bands (like the MRO/CRISM instrument) and high resolution (30 μm/px). While some instrument parameters do not match those of currently operating instruments (e.g. MSL/MAHLI resolution is ~15 μm/px), the multispectral capability allows for determination of rock mineralogy and microtexture at a small scale that is not achieved by existing instruments. It brings the approximate capabilities of the much larger CRISM multispectral imager to a surface instrument with low SWaP. Other instruments, such as the Compact IR Radiometer in Space (CIRiS) of Ball Aerospace, or the far UV imager on board the Southwest Research Institute's LAVA (Lyman Alpha Vision Analyzer) concept also adapt designs from prior, larger instruments, and fit them into smaller form factors.

- Technology and Engineering Developments Enabling the Next Generation of Low-Cost Planetary Exploration: This session was closely related to the theme of the prior talks, but was focused more on technology and engineering developments, in both software and hardware, that will enable future low-cost missions. Topics ranged from novel methods of tracking and landing small entry probes, to assembly and fabrication of structures, in situ, on planetary surfaces. IAA academician Gustavo Medina-Tanco gave an interesting presentation about the assembly of structures on the Moon by self-organized robots. With only two main components—a system of robots capable of self-organization, and a telecommunications, telemetry and deployment module, a payload to demonstrate this capability will be delivered in early 2019 to be launched on Astrobotic's Peregrine Lander. The payload will deploy, on the lunar surface, a swarm of small robots that will assemble themselves into a final, larger structure (e.g. a solar panel) using only simple interaction rules and a few simple sensors. The advantages of this system are clear—assembling infrastructure on the Moon will require multiple small components (each capable of fitting on a launch vehicle) over multiple launches. The ability to 'deploy and forget' these components, letting them assemble themselves, will reduce human labor, and likely cost of such endeavors. Multiple scientific experiments may be performed with swarms having different components, depending on the local need at a specific time. The modularity allows for increased flexibility from a single payload.

At the conclusion of this session was a presentation by a representative of the Jet Propulsion Laboratory Architecture Team ('A-Team'), responsible for mission formulation and concept maturity at JPL. The presentation, on JPL's successful approach to conceiving and maturing mission concepts, was extremely well received, and presented the idea of the 'Concept Maturity Level' (CML)—an analog to the more familiar 'Technology Readiness Level' (TRL)—as a way to classify mission concepts from the most immature, 'cocktail napkin' concepts (CML 1) to mature baseline projects at the end of Phase B (CML 8). Other institutions in attendance had similar programs, and some similarities and differences were discussed among attendees.

- <u>Advanced Concepts for the Next Generation of Low-Cost Missions, Including CubeSats, NanoSats and Others</u>: The entire third day of the conference was dedicated to more advanced concepts in earlier stages of development. These concepts were organized into planetary 'regions': Mars, the Moon, outer planets, and other solar system locations. A number of these concepts competed for NASA PSDS3 funds—some were successful, others were not. Overall, the nearly two dozen presentations covered a wide swath of solar system science that could be accomplished for low cost, and demonstrated the great diversity. Of particular note was a presentation by Professor Jekan Thanga of the Arizona State University on an interplanetary 6U CubeSat mission to Phobos which was designed as the final project of a graduate-level space systems design class at ASU. The mission, designed to understand the geophysical properties of Phobos as well as its evolution, was but one example of the flexibility in architecture and operations that are possible in such a small form factor. Other interesting mission concepts included entry probes to examine small, potentially fluvial features on the Mars surface called 'recurring slope lineae' (RSL), spacecraft penetrators to examine the composition of near earth objects (NEOs), and small atmospheric probes to augment the science obtained from potential future Flagship-class missions to the outer planets.

  The Moon is a popular target for CubeSat and SmallSat missions, as much can be done both from orbit and from small-scale surface operations. The Moon's proximity to the Earth greatly shortens mission lifetime, and allows for more robust communications. Several presentations focused on mapping of the lunar surface, both for volatile detection and exploration of other localized surface features such as magnetic anomalies. A presentation by Dr. Susan Jason of Surrey Satellites discussed one means of a potential commercial-scientific venture, whereby a commercially launched 'mothership' satellite can deliver CubeSats into lunar orbit and then serve as a communications and navigation hub for the duration of the CubeSat missions. Costs, as outlined, appeared competitive to more traditional methods of launch, and there was interest among the audience in the possibility of using such a commercial venture to launch their scientific payloads instead of the more infrequent secondary payload opportunities presently afforded small payloads.

Payloads to other planets were also represented in this session. Because of the greater difficulty getting to the outer solar system, and restrictions on power consumption and data rate by any small spacecraft in this region, many of the low-cost, small satellite concepts presented chose to focus on only one or two fundamental science questions, with payloads solely focused on a specific science question. In many cases, these payloads are designed to make measurements for a period of only a few days to a few weeks—enough to answer only a single question. The SNAP (Small Next-generation Atmospheric Probe) mission concept, which was funded by NASA's PSDS3 program, is designed to be a ride-along payload on a future Uranus mission. It will provide a second entry location for an atmospheric probe. Results from SNAP will answer questions about spatial heterogeneity in the uranian atmosphere between the main probe entry site and the SNAP entry site.

On the first evening of the conference, LCPM-12 held a banquet dinner at the Caltech Athenaeum, in conjunction with an IAA regional meeting and awards ceremony. Prior to dinner, brief words were made by Gregg Vane of the Jet Propulsion Laboratory and Scott Fouse of Lockheed Martin (both IAA academicians), highlighting the relationship between the IAA and the LCPM conference series, as well as the ongoing role of low-cost missions in space portfolios. Following dinner, new members of the IAA were inducted, and recent IAA members received their membership certificates in a ceremony led by Otfrid Liepack of JPL and Dr. Ed Stone of Caltech. Those inducted included:

- Robert Green, CM1
- Frank Webb, CM1
- Janis Chodas, CM2
- Hitoshi Kuninaka, CM2
- Gustavo Medina Tanco, CM4
- Rosaly Lopes, M1
- Robert Pappalardo, M1
- Hajime Yano, M1

On the second evening of the conference, LCPM-12 held an outdoor poster/networking reception with representatives from our industry and commercial partners, demonstrations from conference attendees, and posters from about half of the conference participants. Unlike traditional conferences, where presenters are assigned either an oral or poster presentation, at LCPM-12, all attendees were given the opportunity to do both, as a means to encourage extended conversation among conference participants. Posters were locally printed, at no cost to the attendees, and the response was overwhelmingly positive to the concept. Presentations by commercial vendors showcased their corporate and/or academic products, including a demonstration of spacecraft navigation in virtual reality which was popular among the attendees.

Following the trend of the past few LCPM conferences, LCPM-12 saw a growth in the number and maturity of 'small satellite' presentations (CubeSats and SmallSats) as compared to the more traditional 'low cost' missions (i.e. NASA Discovery Class, ESA S-Class). By the time of the next LCPM conference, several planetary CubeSats will have launched, and data will be available from these missions. The community is eager to see results from these projects, and to evaluate the actual cost-benefit ratio of doing science with low-cost missions. If it can be demonstrated that valuable science is being performed by these early missions, it will greatly encourage subsequent launches, and involvement by national space agencies, which have been focusing on more cost-efficient measures for planetary exploration.

Applications for subsequent iterations of the LCPM conference (LCPM-13 and LCPM-14) will be submitted by CNES and JAXA, respectively, and it is thought that subsequent conferences will be held in France and/or Japan in 2019 and 2021.

Details about the conference, and copies of most presentations may be found on the conference website at http://lcpm12.org.

APPENDIX A:

Dates and locations of prior LCPM conferences

1st	1994	Laurel, Maryland, USA
2nd	1996	Laurel, Maryland, USA
3rd	1998	Pasadena, California, USA
4th	2000	Laurel, Maryland, USA
5th	2003	Noordwijk, The Netherlands
6th	2005	Kyoto, Japan
7th	2007	Pasadena, California, USA
8th	2009	Goa, India
9th	2011	Laurel, Maryland, USA
10th	2013	Pasadena, California, USA
11th	2015	Berlin, Germany
12th	2017	Pasadena, California, USA