Cubesats in Cislunar Space

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ABSTRACT

Within the next three years, at least 15 deep space cubesat 'prototypes' will have been launched, testing the viability of cubesat paradigm in deep space. Three of the EM1-deployed cubesat missions, the first de facto deep space cubesat 'cluster', will be science requirements driven lunar orbiters with remote sensing instruments for lunar surface/subsurface volatile characterization. These include: Lunar Ice Cube (1-4 micron broadband IR spectrometer and microcryocooler, volatile distribution as a function of time of day), Lunar Flashlight, (active source laser and NIR detector, polar surface ice), and LunaH-Map (neutron spectrometer, polar ice to 1 meter).

INTRODUCTION

Unlike their earth-orbiting predecessors, deep space cubesats are required to have the full functionality, and active control systems, of any spacecraft operating in deep space. 15 6U cubesats with diverse payloads entering deep space over the next two years have been (MarCO) or are being built (EM1 13), effectively 'prototypes' for deep space cubesats. Three of them, Lunar Ice Cube, Lunar Flashlight, and LunaH-Map, are science requirements-driven lunar orbiters with the goal of increasing our knowledge of lunar volatiles, acting as the first de facto deep space cubesat cluster.

MarCO AS PATHFINDER

The very first deep space cubesats to be deployed in deep space were the MarCO duo Wall-E and Eva. They were launched as secondaries with NASA's InSight, a Mars Lander designed to study the Martian interior, and deployed from InSight after insertion into a Mars flyby trajectory. They are technology demonstrations, designed to test the dual band communication system which includes a UHF system for 'local' real-time communication and tracking of InSight during Entry, Descent, and Landing (EDL) as well as a compact X-band communication system for relaying that information to Earth. MarCO will demonstrate two technologies key to future deep space cubesats, including most of those being deployed form EM1: both a deployable high gain X-band antenna and a compact X-band software defined radio (IRIS). Wall-E has already used a compact wide-field camera to take a picture of the Earth-Moon system from space. Despite a small leak in one of the propulsion systems, JPL engineers are optimistic that one or both cubesats will be able to follow, receive and transmit signals from InSight during its EDL.

CURRENT CONTEXT

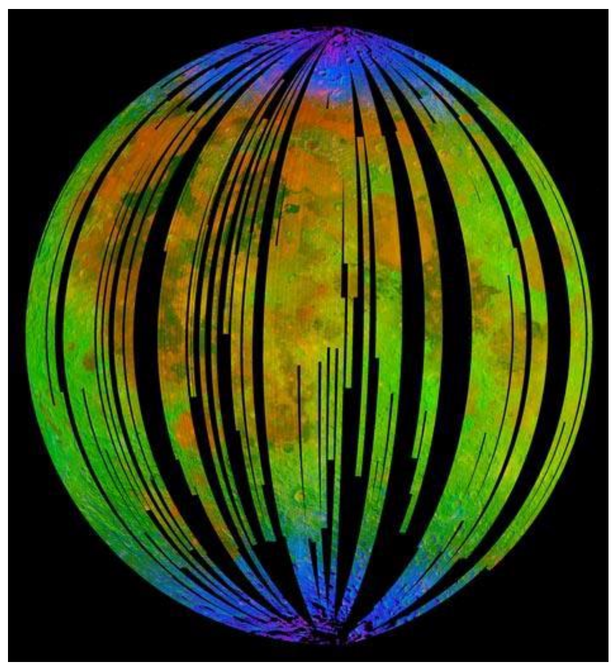


Figure 1. Water and Hydroxyl on the Moon indicated by blue, deep orange, deep green. Credit: ISRO/NASA/JPL Chandrayaan-1 Mission.

New discoveries as well as trends over the last decade have caused increasing interest in the Moon.

Findings from several lunar missions nearly a decade ago played a major role in modifying our understanding of the role and potential availability of resources on the

Moon. The Lunar Crater Observation Sensing Satellite (LCROSS) observed abundant water and ice released from the floor of polar crater Cabeus at impact [1,2]. Unexpectedly, an OH feature, indicating the presence of an OH veneer extending from poles to equator, was derived from IR spectral absorption features detected by instruments onboard Chandrayaan (**Figure 1**), Deep Impact (**Figure 2**), and Cassini [3,4,5]. These findings suggest that the Moon has both water and OH diurnal cycles that are global and not yet fully verified and understood. Furthermore, the apparent presence of water and OH, even at mid-latitudes [6], and of water associated with pyroclastic deposits [7] has a profound effect on our understanding of the nature of surface chemistry on all airless exposed bodies. Specifically, if such OH and water is of solar wind origin, then the observations suggest that ~1 keV protons interacting with any oxide-rich surface will thus generate OH via surface interactions. In essence, the discovery of lunar OH at lunar latitudes as low as 30 degrees could imply that all exposed oxide-rich bodies are miniature water and OH factories, a finding with implications for In Situ Resource Utilization. Further reconnaissance of our nearest neighbor, the Moon, will be essential to determine the viability of such a proposition.

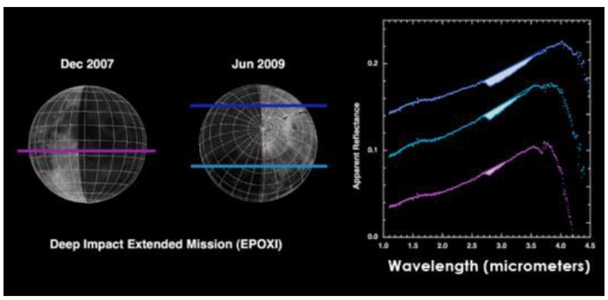


Figure 2. Absorption feature depth (abundance) correlated with time of day. Credit: NASA/JPL/Caltech/UMD Deep Impact Mission.

As Low Earth Orbit, the previous domain of cubesats, has become a virtually financially achievable and sustainable venue, attention has turned to cislunar space as the next 'conquerable frontier' as illustrated by these activities planned or underway:

- USA: recent lunar initiative supporting the development of lunar payloads and commercial landers and orbiters to carry these payloads to the Moon
- China: plan for long-term cislunar industrial development and space-based power
- Russia: plan for lunar polar lander, orbiter, sample return, and joint (with USA) orbiting spaceport
- Europe: Collaboration with Russians and Chinese on International Moon Village
- Japan, India: plan for lander, rover, sample return, tech demos in support of long-term base.
- Commercial Interests: developing lunar destination launch services, landers, and orbiters to start as early as 2019.

LUNAR CUBES PLANNED

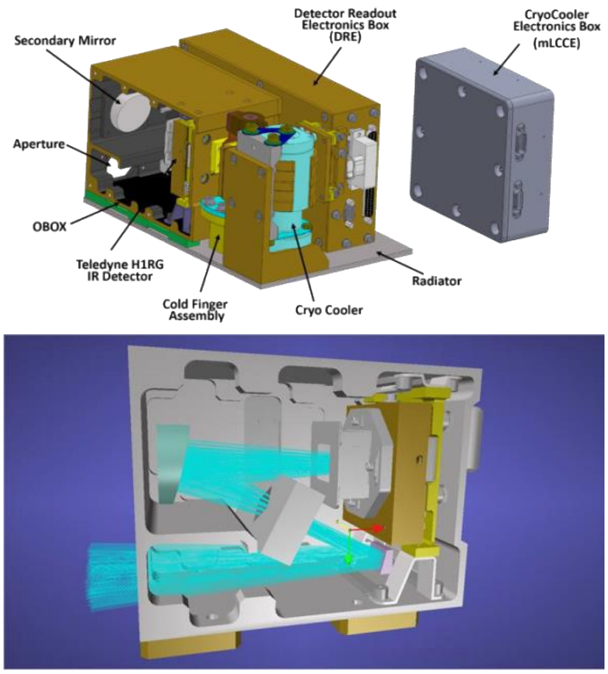
Table 1: Planned Cislunar Missions

Mission	Goal	Program
Lunar Ice Cube	Orbit, any form water	NASA HEOMD
Lunar Flashlight	Orbit, South Pole Ice	NASA HEOMD
LunaH-Map	Orbit, South Pole Ice	NASA/SMD
SkyFire	flyby, thermography	NASA HEOMD
Omotenashi	impact, radiation	JAXA (on EM!)
Team Miles	CubeQuest	NASA STMD
CUE3	CubeQuest	NASA STMD
Cislunar Explorers	CubeQuest	NASA STMD
LUMIO	L2, Meteoroids	ESA LUCE
VMMO	Orbit, Shackleton	ESA LUCE

Out of the 13 cubesats to be deployed by EM1 sometime during 2020, 8 are specifically designed for lunar or cislunar operation: Lunar Ice Cube, Lunar Flashlight, and LunaH Map, all of which will be described in more detail below. SkyFire is a Lockheed Martin flyby which will perform IR thermography and demonstrate a new propulsion system, and Omotenashi is a JAXA-sponsored semi-hard impactor and radiation environment monitor. NASA CubeQuest challenge selectees Team Miles (Tampa HackerSpace), CUE3 (U Colorado), and Cislunar Explorers (Cornell) will demonstrate communication and propulsion technologies in cislunar space. The compact Ion Analyzer and energetic neutral imagers instruments of the proposed Hydrogen Albedo Lunar Orbiter (HALO) received further development funds, through the NASA SIMPLEx program, and compact surface instruments were proposed for NASA's Development of Advanced Lunar Instruments (DALI) program, to be selected later in 2018. Meanwhile, two 12U cubesat missions, LUMIO (Meteoroid Impact Detection from L2) and VMMO (Volatiles/Mineralogy Shackleton Crater Orbiter) were selected for the ESA LUCE program

THE LUNAR CUBESAT 'CLUSTER'

Lunar Ice Cube, Lunar Flashlight, and LunaH-Map provide complimentary measurements essential in understanding water origin, cycle, and dynamics on the



Moon (**See Table 1**).

Figure 3: Lunar Ice Cube BIRCHES spectrometer (above) and ray tracing (below) with components as described in text.

Lunar Ice Cube

The Lunar Ice Cube Mission goal [8] is the determination of abundances of forms and components of water (e.g., adsorbed water, bound water, ice, hydroxyl). as a function of time of day. BIRCHES (**Figure 3**) (Broadband IR Compact High-resolution Exploration Spectrometer), the Lunar Ice Cube payload, is a compact version (2 U, 3 kg, 10-20 W) of GSFC's OVIRS on OSIRIS-REx. The point spectrometer is designed to provide hyperspectral measurements of volatile-related features in the 1 to 4 □ _region, especially the so-called '3 micron band', consisting of several water-related features. LVF. Previous lunar orbiting Near IR spectrometers did not provide measurements beyond 3 microns. The optics box has an uncomplicated design, consisting of optically coated all aluminum components, including two off-axis mirrors, separated by an adjustable field stop allowing change the footprint dimension by an order of magnitude, to adjust for variations in altitude and/or incoming signal. The AIM microcryocooler provides the <115K environment needed for the detector, a flight spare Teledyne H1RG MCT. The optics have a dedicated radiator to maintain a <220K environment for the optics during data taking. Lunar Ice Cube requires a very elliptical equatorial periapsis orbit with a repeat cycle that allows coverage of the same illuminated swaths at different times of day over the course of 6 months to achieve its goals.

The 6U spacecraft (**Figure 4**) utilizes and demonstrates the functionality for deep space of the Busek High ISP RF Ion Engine for propulsion, the BCT attitude knowledge and control system (XACT Star Tracker, Reaction Wheels, IMU), version 2.1 of the JPL Iris ranging transceiver, and the inexpensive Space Micro flight computer, designed to be radiation tolerant. LunaH Map will also fly the same Busek engine, and both LunaH Map and Lunar Flashlight the Version 2.1 Iris communication subsystem.

Lunar Ice Cube will fly in a nearly polar, highly elliptical, equatorial periapsis orbit designed to provide repeat coverage of the same orbital swaths systematically at varying times of day during up to six consecutive lunar cycles (**Figure 5**). In this way, such overlapping coverage will be provided for up to 10% of the lunar surface across all latitudes.

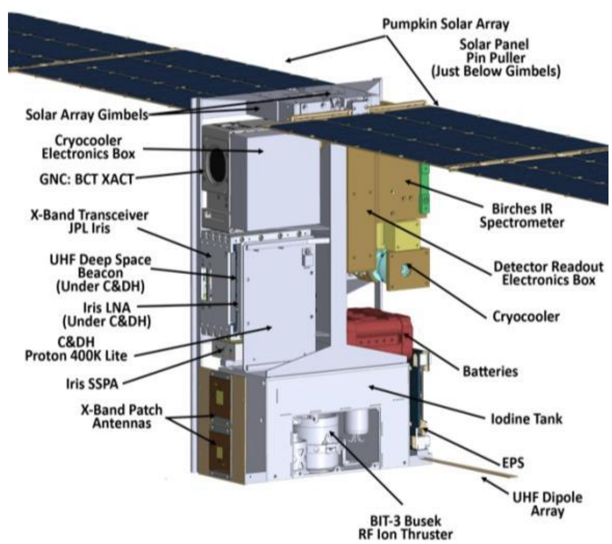


Figure 4: Lunar Ice Cube 6U spacecraft as described in the text. Note BIRCHES spectrometer and BUSEK propulsion system, both tech demos for this mission.

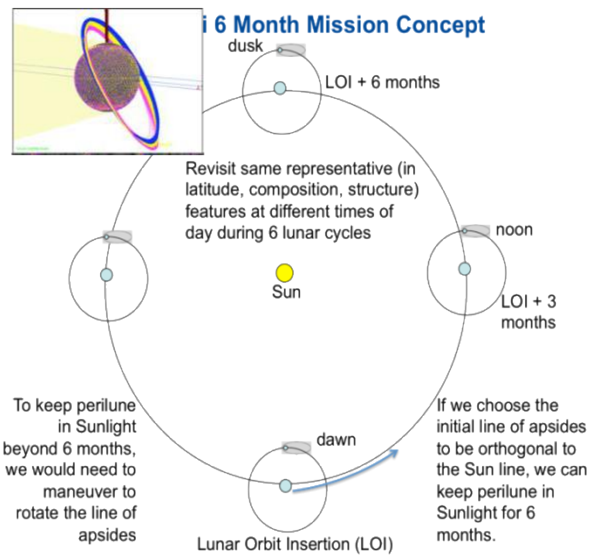


Figure 5: Lunar Ice Cube Mission Concept as described in text.

Lunar Flashlight and LunaH-Map

LunaH-Map [9] (**Figure 6**) and Lunar Flashlight [10] (**Figure 7**), both 6U cubesats, are in very elliptical, long period (10 hours for LunaH Map, 5 days for Lunar Flashlight), low (<10 km for LunaH Map, 14 km for Lunar Flashlight), south polar periapsis orbits for 2 months to search for evidence of ice in 'cold traps' at the poles.

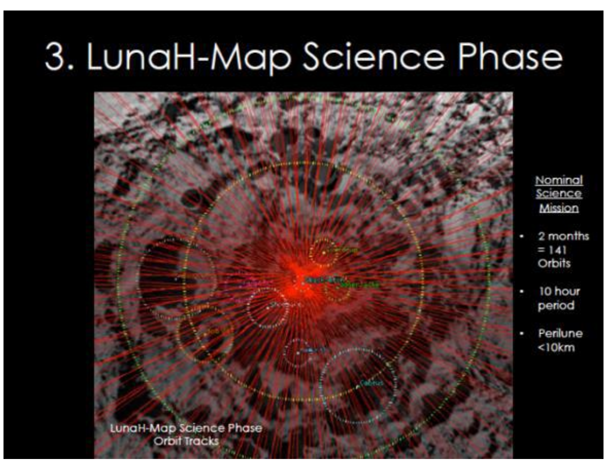


Figure 6: LunaH-Map Science Measurement Coverage for South Pole

LunaH Map will search within two degrees of the poles for surface or subsurface (down to 1 meter) ice with a resolution of 7.5 km. Its two compact neutron spectrometers, utilizing a new material (CYCL) for neutron detection, are designed to observe suppression in neutron flux (low epithermal neutron flux) indicating the presence of protons within 1 meter of the surface. Such detections, associated with permanently shadowed regions or burials from recent impact events, are likely to be associated with ice as opposed to solar wind (proton) implantations at the (illuminated) surface.

Lunar Flashlight will observe permanently shadowed areas within ten degrees of the poles with a spatial resolution of 1 km. Lunar Flashlight utilizes near IR lasers emitting at wavelengths associated with water ice (1.50 and 1.85 microns) absorption and the reflectance continuum (1.06 and 1.99 microns). Actively illuminating the surface at nadir, the laser 'transmitters' are aligned with optical receivers (InGaAs near IR detectors) which detect the signal reflected from the surface. Decrease in the returning signal 1.04/1.50 or 1.85/1.99 ratios indicates an absorption feature and thus the presence of surface ice.

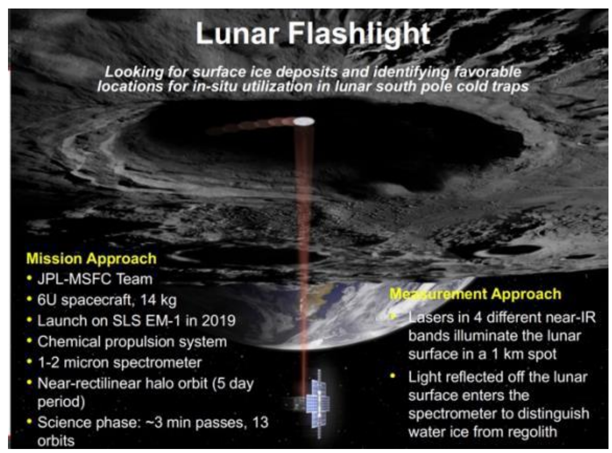


Figure 7: Lunar Flashlight mission concept as described in text.

NEXT STEP: THE LUNAR SURFACE

Credible opportunities for delivery of small payloads to the lunar surface or lunar orbit via commercial landers are emerging in the coming decade. The latest scientific findings (See CURRENT CONTEXT) indicate the presence of water, a useful resource, in the regolith of Moon and other atmosphereless bodies. Further reconnaissance, thus more extensive in situ observation, is essential to establish whether water is an extractable resource. Characterization of the highly interactive volatile/field/energetic particle/dust environment of the lunar surface and subsurface, requires continuous (day/night, multiple cycle) operation. The challenges in achieving such goals, particularly utilizing low-cost, compact, deliverable packages, are described in CURRENT DRIVING REQUIREMENTS. Surface networks of stationary or mobile platform instruments such as Infrared (absorption feature) Imagers, energetic particle analyzers, mass spectrometers, electric field instruments or magnetometers, interior sounders, could certainly be envisioned as part of this network [11].

CURRENT DRIVING REQUIREMENTS

The Moon, from orbit or on the surface, is a challenging operational environment. Greater utilization of cislunar space will require an infrastructure we do not yet have in place.

Environmental Mitigation

The temperature range varies from 400 K to 90K at the equator to 150K to 50K in subpolar regions over each lunar cycle (28 days, except near the poles where it is one year), with the most rapid changes at dawn and dusk (terminator crossings) [12]. Thermal protection systems must consider not only the sun but thermal emission from the surface, which is covered with a regolith with very low thermal conductivity. This makes operating in low orbit or on the surface very challenging. Special radiators/reflector systems, based on those used on Apollo, have already been developed for this purpose. On the other hand, the biggest thermal challenge is operating, or even surviving, during lunar night with compact, low-cost surface payloads. The conventional approach, requiring radioisotopes, is relatively costly and inefficient.

In addition, movement of any kind on the surface will stir up lunar regolith particles at the surface, causing them to act as a contaminant on surrounding surfaces [13]. The behavior of lunar dust, described as 'abrasive Velcro', results from the extremely complex surface morphology of the elongated, interlocking, glassy shards, which, acting as insulators, utilizing the nooks and crannies as sources and sinks for charge. Mechanical brushing used in the Apollo program damaged the astronaut's spacesuits almost to the point of puncture. Proposed electrostatically-based approaches have not yet been attempted. Mechanisms that could come in contact with the regolith need to be protected, especially if longer term use is contemplated.

Active Control Systems

The Moon has numerous pronounced mass anomalies (mascons), and thus gravitational anomalies. These result from the infilling of the holes (craters) left by earlier large impact events with later stage volcanic material denser than the crust. Robust propulsion and attitude control systems are needed to support the station keeping, momentum dumping, and increased Delta V required to maintain most orbits. The exceptions are the polar, nearly circular, low altitude orbits called 'frozen orbits'.

Communication

Bandwidth is a limited resource in deep space, even in cislunar space. Mission and Program architectures that support dual communication capability (local and distant) on each spacecraft, communication 'hubs' or low-cost distributed and replaceable networks will be crucial to support the planned activity over the next decade. Smart onboard processing utilizing, for example, change detection algorithms for minimizing the downlink requirements, is highly desirable.

Transportation

To date, though we have had many lunar missions, we haven't had an infrastructure that supports regular lunar visits. The success of the commercial sector at sending the first landers and orbiters to the Moon within the next two years as planned is crucial here. Astrobotic, Masten, and MoonEx seem the most likely candidates. Beyond that, the setting up of an efficient means of transportation between the Earth and Moon, perhaps through the use of cycling orbits as proposed by Buzz Aldrin, will be required.

LESSONS LEARNED

The first deep space cubesat programs have provided some valuable lessons to date, even though not as yet completed. Deep space cubesats have to face many more challenges than Earth-orbiting predecessors, and the science and/or technology requirements have been more stringent.

- The first deep space cubesats, being developed simultaneously, are prototypes, and costs can't be extrapolated directly from LEO cubesats built to date. even when a 'fudge factor' (like a friendly order of magnitude) is built in. Attempts to do so have so far resulted in underestimated cost. Earth Orbiting cubesats can utilize the Earth's magnetic and gravitational fields in lieu of active control systems (propulsion, attitude control), operate in a less extreme (thermal, radiation, lifetime) environment, and can utilize extensive and relatively close-at-hand ground-based antenna system or build a dedicated antenna relatively inexpensively. Costs for future deep space cubesats will be lower, and interpolatable, after these prototypes are developed and operated.

- The first deep space cubesats have been universally driven by more stringent, programmatically-set mission requirements, scientific and/or technological. Thus, the appropriate level of documentation and testing, and thus development paradigm and costs have yet to be established, though teams are currently experimenting with different approaches.

- As all working on the first generation deep space cubesats have discovered, costs aren't universally scalable based on size of payload or development model. Flight software development, mission operations, and science data management costs depend on mission complexity to a large extent, and deep operations are intrinsically more complex than Earth operations.

- The harnessing by deep space missions of the cubesat paradigm, with rapid and lean development and operation, compactness, and standardization of deployment packaging and interfaces as touchstones, will require 1) sharing of personnel and equipment resources and tools, 2) automated, electronic capture systems for testing and documentation, and 3) a new track for deep space missions which capitalizes on emerging communication and transportation services, and prioritizes rapid technology qualification and/or reasonable cost multi-platform concepts. Further lessons and successful models for a deep space cubesat paradigm will emerge through the collaboration of those already using the cubesat paradigm to create an innovative and tailored solution with a standard platform for deep space missions.

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