LUNAR FLASHLIGHT: MAPPING LUNAR SURFACE VOLATILES USING A CUBESAT.
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Introduction: The scientific and economic importance of lunar volatiles extends far beyond the question "is there water on the Moon?" Volatile materials including water come from sources central to NASA's strategic plans, including comets, asteroids, interplanetary dust particles, interstellar molecular clouds, solar wind, and lunar volcanic and radiogenic gases. The volatile inventory, distribution, and state (bound or free, evenly distributed or blocky, on the surface or at depth, etc.) are crucial for understanding how these molecules interact with the lunar surface, and for utilization potential.

The abundance and distribution of lunar water must be addressed before robots or humans can locate and extract it. Shadowed regions near the lunar poles maintain temperatures perennially below the sublimation point for water and many other volatiles of scientific and exploration interest [1]. The Moon Mineralogy Mapper (M3), EPOXI and Cassini instruments found both water (H_2O) and hydroxyl (OH) molecules on the lunar surface at high latitudes, indicating that trace amounts of adsorbed or bound water water are present [2-4]. Narrow-band reflectivity data from LRO also suggests volatiles may be present on the surface, yet surface roughness effects cannot be ruled out [5,6]. Regions of enhanced hydrogen abundance mapped by neutron spectrometers on board the Lunar Prospector and Lunar Reconnaissance Orbiter Spacecraft suggest the presence of subsurface ice in the polar regions, but the distribution is difficult to reconcile with thermal maps [7,8]. As we reach the limits of existing data, it is clear that a further investigation and mapping of water at the lunar surface to determine whether it can be considered an extractable resource, particularly in the lunar polar regions targeted for their subsurface ice reservoirs [e.g. 8-10]. Here, we describe an innovative, low-cost concept for such a mapping mission based on work done at the Jet Propulsion Laboratory, UCLA, and Marshall Space Flight Center, which was recently propsed to NASA's FY2014 Advanced Exporation Systems (AES) call.

Mission Overview: For this call, we focused on a non-optimized "Lunar Flashlight" concept on a 6U CubeSat bus. The spacecraft would be launched and delived as a secondary payload on the first test flight (EM1) of the Space Launch System (SLS) scheduled for 2017. The CubeSat then maneuvers to its lunar polar orbit and uses its solar sail as a mirror to steer sunlight into shaded polar regions while a spectrometer measures reflection diagnostic of surface compositional mix among rock/dust regolith, H_2O, CO_2, CH_4, and possibly NH_3.

Payload: IR spectroscopy has already proven useful in mapping lunar volatiles as demonstrated by M3 on Chandrayaan-1. As the light source for M3 was direct solar illumination, M3 was unable to investigate permanently shadowed areas. Lunar Flashlight, however, will utilize an 8-m solar sail to reflect ~50 kW of sunlight to the lunar surface, enabling IR spectroscopy of shadowed areas. The solar sail is flat to ~ 0.5 deg; when added to the 0.5 deg divergence angle of the sun, this provides a beam with ~ 1 deg divergence, illuminating a spot of ~400 m in diameter from an altitude of 20 km (perilune). Spectral modeling indicates that a point spectrometer with only four spectral bands can distinguish between dry regolith, H_2O, CH_4, and CO_2 ices, with a signal-to-noise ratio better than 100.

This instrument, consisting of a lens, dichroic beamsplitters and multiple single-element detectors, occupies 2U of the 6U CubeSat bus. The spectral bands are centered at wavelengths of 1.0, 1.4, 1.5, and 1.6 µm. For an orbital velocity of ~2 km/s (at perilune), an integration time of 0.2 s provides spatial sampling matched to the diameter of the illuminated spot on the surface (400 m). In the spectral band of width 0.2 µm centered at 1.5 µm (for example), the sail provides a source flux of ~2 x 1022 photons/s. For a lunar reflectance of 10%, a spectrometer at a range of 20 km with an aperture diameter of 2 cm, detector diameter of 1 mm, and system quantum efficiency of 0.5 will detect ~ 5 x 107 photons in this band per 0.2 s exposure. For an HgCdTe detector with diameter of 1 mm and cutoff wavelength of 1.7 µm, maintaining the dark current below the signal (< 5 x 107 e) requires cooling the detector to 210 K, and would provide an SNR ~ 3000 (accounting for both photon noise and dark noise).

Flight/Mission System: The Lunar Flashlight 6U spacecraft is derived from three predecessor systems--JPL's INSPIRE, Morehead State's Cosmic X-Ray Background NanoSatellite (CXBN), and JPL's experience with imaging spectrometers, including M3. The CubeSat bus will utilize mostly COTS elements such as the batteries, the CPU board, solar panels, star tracker and reaction wheels. A deployable solar sail/reflector is used from the small business Stellar

Exploration, based on their aluminized Kapton LightSail [11], scaled up to longer booms and 2U stowage volume. JPL will provide the INSPIRE-developed and tested Iris that provides timing, telecom and navigation at X-band.

Mission/Trajectory Concept: The Lunar Flashlight spacecraft would be ejected from SLS during its trans-lunar flight, and acquires the Sun for power using sun sensors and reaction wheels. The CubeSat would then be oriented in the appropriate direction for solar sail deployment from which to begin deflecting the trajectory toward a multiple lunar and earth swingby transfer and loose capture into a lunar polar orbit in 1-2 months. After lunar capture, the CubeSat would spiral down to the final elliptical polar orbit. From here, measurements begin, and apolune would be "staked" while perilune is lowered with care to 20 km, the primary data-taking altitude. The sail would be maneuvered to provide orbital changes, and to offset its own thrust produced while it is used to reflect sunlight into the target craters. A small steering mirror in front of the spectrometer aligns the field of view with the spot illuminating the lunar surface, moving at orbital speed, for 5-10 minutes of data taking per orbit. Preliminary geometric analysis of visibility indicates that all permanently shadowed locations are viewable using Lunar Flashlight at some times during a lunar month, and all locations within ~9 deg of the pole can be illuminated during any overflight. After sufficient coverage of all targeted craters, the orbit can be stepped down farther, e.g., to 10 km, to improve location determination of any discovered ice exposures. Alternatively, the perilune could be raised, and apolune lowered over the opposite pole, in order to obtain a similar dataset for each pole, over a period of months. The longer elliptical orbits could be planned to allow sufficient maneuvering time to maintain the orbit between successive polar passes, and to downlink the data.

Launch Integration and Deployment: The project works closely with MSFC to address launch environmental consitions, payload-to-launch vehicle integration and SLS Program coordination on required payload integration activities including interface documentation, models, schedules, and overall issue resolution to ensure successful integration of the project into the SLS mission. MSFC will also provide a 6U CubeSat deployer certified to SLS environments and meeting all safety requirements. Flight certification of the spacecraft and its components will be performed by JPL to SLS specs provided by MSFC.

Conclusions: In order to answer NASA's Human Exploration goals, caputured by lunar Strategic Knowledge Gap (SKG) I-D "Composition/quantity/distribution/form of water/H species and other volatiles associated with lunar cold traps" [12], we propose a low-cost CubeSat-based method of locating, mapping, and identifying the composition of surfacial ice deposits in the Moon's polar shadowed regions. Development of the Lunar Flashlight CubeSat concept leverages JPL's Interplanetary Nano-Spacecraft Pathfinder In Relevant Environment (INSPIRE) mission, MSFC's intimate knowledge of the Space Launch System and EM-1 mission, Morehead State University's education-driven CubeSat program, small business development of solar sail and electric propulsion hardware, and JPL experience with specialized miniature sensors. Together, these components demonstrate a path where 6U CubeSats could, at dramatically lower cost than previously thought possible, explore, locate and estimate size and composition of ice deposits on the Moon. By addressing the polar volatiles SKG, Lunar Flashlight could enable a low-cost path to In-Situ Resource Utilization (ISRU) based on operationally useful deposits (if there are any), which is a game-changing capability for expanded human exploration.

A follow-on mission could then perform mini-LCROSS-style measurements, targeting a leader-follower nanosat pair, where the follower directly measures the plume of the leader's impact at the most promising locations revealed by Lunar Flashlight. Such confirmation could then ensure that targets for more expensive in-situ rover-borne measurements would include volatiles in sufficient quantity and near enough to the surface to likely be operationally useful.

Finally, Lunar Flashlight could provide an experience-based CubeSat mission architecture, hardware, and software, that can be applied to any NASA objective where delivering a 2U-class instrument within the inner Solar System can yield valuable results for human exploration, planetary science, heliophysics, and other applications.

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