LUNAR FLASHLIGHT: ILLUMINATING THE LUNAR SOUTH POLE

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Abstract: Lunar Flashlight is an innovative, small NASA mission to be launched as a secondary payload on the Space Launch System Exploration Mission 1 (EM-1). This highly mass- and volume-constrained satellite will demonstrate several technologies for NASA, including the use of "green" propellant, the ability for a CubeSat-sized satellite to perform science measurements beyond low Earth orbit, and the first planetary mission to use multi-band active reflectometry from orbit. Lunar Flashlight will detect and map water ice in permanently shadowed regions of the lunar south pole by measuring surface reflectance at multiple wavelengths. Mapping and quantifying lunar water ice addresses one of NASA's Strategic Knowledge Gaps to understand the lunar resource potential for future human exploration of the Moon.

Index Terms: To be determined

Introduction

Recent reflectance data from LRO instruments suggest water ice and other volatiles may be present on the surface in lunar permanently-shadowed regions, though the detection is not yet definitive. Understanding the composition, quantity, distribution, and form of water and other volatiles associated with lunar permanently shadowed regions (PSRs) is identified as a Strategic Knowledge Gap (SKG) for NASA's human exploration program, projected to visit the lunar south pole in the next decade. These polar volatile deposits are also scientifically interesting, having potential to reveal important information about the delivery of water to the Earth-Moon system.

Lunar Flashlight is a very small satellite (6U bus, or 12×24×36 cm) managed by the Jet Propulsion Laboratory that will determine the presence or absence of exposed water ice and map its distribution within the PSRs at the lunar south pole. Lunar Flashlight was selected in 2014 by the NASA Advanced Exploration Systems (AES) program within the Human Exploration and Operations Mission Directorate (HEOMD); the mission is currently funded as a technology demonstration mission within NASA's Space Technology Mission Directorate portfolio. Lunar Flashlight will be one of 13 secondary payloads launched on the first test flight (EM-1) of the Space Launch System (SLS), currently scheduled for 2020. After being ejected by SLS, Lunar Flashlight uses "green" propellant to maneuver into a low-energy transfer to lunar orbit and achieve a perilune of 10-30 km above the south pole for data collection. The Lunar Flashlight mission is will demonstrate technologies for NASA such as green propulsion and active laser spectroscopy while proving the capability of performing a planetary science investigation in the cubsat form factor.

Science and Payload

Water on the Moon is both a record of science and a resource for exploration. Volatile compounds are fundamental tracers of a planetary body's origin, evolution, and interaction with its space environment. The observed abundance and chemical inventory of condensed volatiles may also reveal a history of dynamical exchange among different regions of the Solar System. Near the poles of the Moon, large areas of perennial (or "permanent") shadow create cold traps, where volatiles would be thermally stable for billions of years. Permanently shadowed regions (PSRs) may therefore hold a record of volatile delivery, transport, sequestration, and loss through geologic time [1, 2]. In addition, water could be an important target of in situ resource utilization (ISRU), where O_2 and H_2O for life support or H_2 and O_2 for fuel and propellant could be derived from deposits of water ice [3-5].

Lunar polar water ice consists of two reservoirs: deeply buried ice deposits, and surface water frost. The Clementine, Lunar Prospector, and Lunar Reconnaissance Orbiter missions made observations consistent with ice deposits cm- to meters-deep in PSRs with concentrations ~1% H2O by mass [6-9], but not all PSRs contain water ice signatures. The Lunar CRater Observation and Sensing Satellite (LCROSS) mission excavated and heated 10's of m of regolith, revealing 5-7 wt% of H_2O along with a comet-like array of volatiles [10]. At the lunar surface, spectroscopic and albedo measurements from the Lunar Reconnaissance Orbiter and Moon Mineralogy Mapper show surface reflectance properties consistent with water frost at concentrations ranging from ~0.1 up to ~10 wt% in the south polar PSRs, with a patchy distribution [11-13]. However, the distribution of apparent water frost at the surface does not match the subsurface distribution, and neither is its occurrence proven everywhere temperatures are cold enough to permit trapping of water molecules [14]. Current data are not yet sufficient to conclude the form, quantity, or distribution of lunar H_2O at concentrations sufficient for in-situ resource utilization (IRSU), or to predict the distribution of ice at scales of a rover or human landed mission.

Because of this uncertainty, and the potential utility of water as a resource to human exploration, NASA identified a Strategic Knowledge Gap (SKG) for Human Exploration to understand the composition, quantity, distribution, and form of water and other volatiles associated with PSRs [15]. The Lunar Flashlight mission will make definitive detections of water ice within PSRs. Lunar Flashlight carries an active laser illumination system and a multi-band reflectometer to measure surface reflectance in permanently shadowed regions at four near-IR wavelengths diagnostic of water ice presence. Derived reflectance and water ice band depths will be mapped onto the lunar surface in order to identify locations where H_2O ice is present in concentrations above 2 wt%, at the scale of ~10 km/pixel or smaller.

The Lunar Flashlight illumination system uses stacked laser diode bars to emit energy pulses at four discrete wavelengths in rapid sequence, while a receiver system detects the reflected light. We optimized the laser wavelengths to distinguish water ice absorption bands from dry lunar regolith using two pairs of molecular absorption bands and continuum measurements (Fig. 1). The selected wavelengths are 1.064 (-0.060 / + 0.230) µm & 1.850 (-0.030 / +0.020) µm for continuum

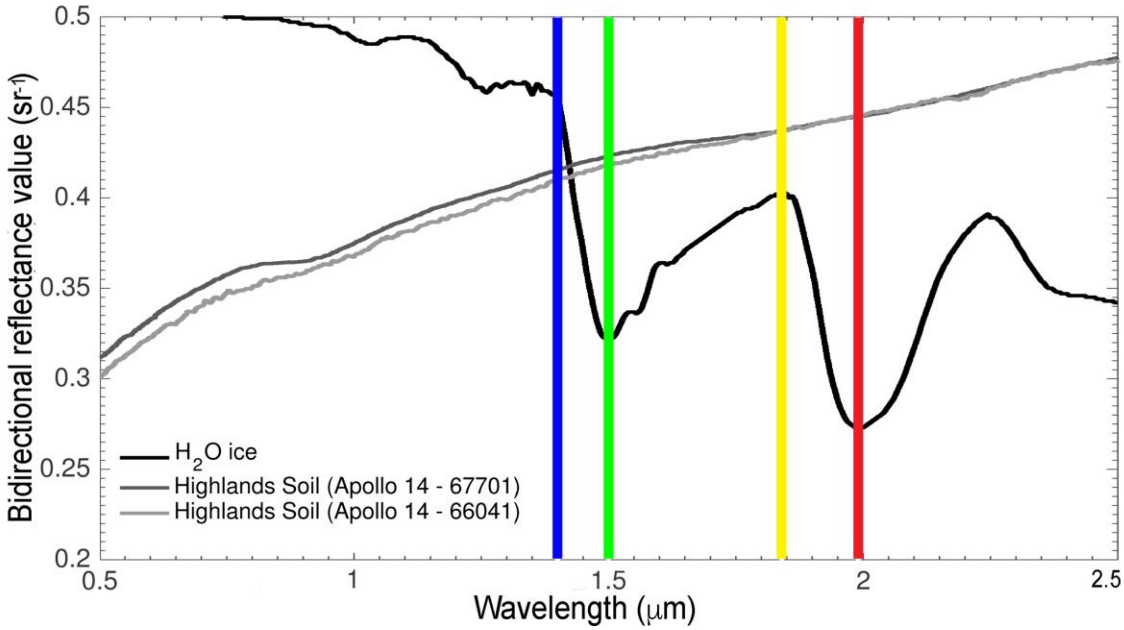

Fig. 1. Lunar Flashlight uses four-point spectroscopy to distinguish dry regolith from water ice frost. Two of the four wavelengths (~1.495 µm and ~1.99 µm) correspond to overtone vibrational absorption features for water ice, while the two other wavelengths (~1.064 µm and ~1.85 µm) correspond to nearby continua. The measurement will ratio the reflectance value in the absorption features to the continuum to determine water ice abundance.

measurements and 1.495 (-0.015 / +0.015) µm & 1.990 (-0.020 / +0.025) µm for absorption bands. The Lunar Flashlight 1.064 µm laser is the same wavelength used by the LOLA instrument, potentially enabling a tie point of absolute surface reflectance, though at a different spatial scale.

The laser diodes are procured from DILAS, Inc.; the continuum bands are off-the-shelf procurements and custom laser epitaxies were grown for the water band wavelengths. The diode lasers, supplied with 45 A current from batteries, emit 14-72 W (depending on wavelength). 99.6% of the emitted energy is encircled within a full-angle of 17 mrad. The receiver is an aluminum, off-axis paraboloidal mirror with a focal length of 70 mm, which collects the reflected light from the lunar surface onto a single-pixel InGaAs detector with a 2-mm diameter, providing a 20-mrad field of view. The detector temperature is cold-biased and stabilized by a heater. See [16, 17] for a more thorough description of the design and characterization of the Lunar Flashlight multiband reflectometer.

In nominal operation, the LF lasers fire sequentially for 1-6 ms each, followed by a pause of 1-6 ms with all lasers off. The optical receiver collects and measures the light reflected from the lunar surface. The measurement with all lasers off quantifies the background, which is the sum of detector dark current, thermal emission from the receiver itself incident on the science detector, and solar illumination reflected from the lunar surface and detected by the instrument from both inside and outside its FOV. In order to increase the SNR, the measurements can be added along-track for each spectral band to create the desired mapping resolution (~10 km). The total duration of laser firing per pass will be approximately 2-3 minutes during the closest approach. By repeating these measurement over multiple points, Lunar Flashlight will create a map of surficial ice concentration that can be correlated to previous mission data and used to guide future missions. All calibrated data and derived data products will be publicly archived in NASA's Planetary Data System (PDS).

Mission Design

Lunar Flashlight and the other EM-1 secondary payloads will be launched within a Secondary Payload Deployment System (SPDS) mounted in the Orion Stage Adapter (OSA) of the Block -1 SLS [18]. Tyvak Nano-Satellite Systems will integrate each payload into a PSC C50 dispenser and deliver it for integration into the SPDS. After launch and Orion separation, the SPDS will deploy payloads at several "bus stops" along the SPDS trajectory. The SPDS will command the dispenser door to open, allowing the spring-loaded dispenser plate to push the payload into space.

Lunar Flashlight will be dispensed at the first available "bus stop" for EM-1 cubesats, at about 36,000 km above Earth. It must maneuver via a low-energy transfer to a polar lunar orbit insertion point. The spacecraft will detumble, deploy its solar panels, and make initial contact with Earth. It will conduct an initial 20 km/s trajectory correction maneuver (TCM) to avoid escaping the Earth-Moon system and place it on a looping trajectory around the Earth and Moon (Fig. 2). A total of three loops are required to achieve polar orbit insertion with the required sun geometry. As the

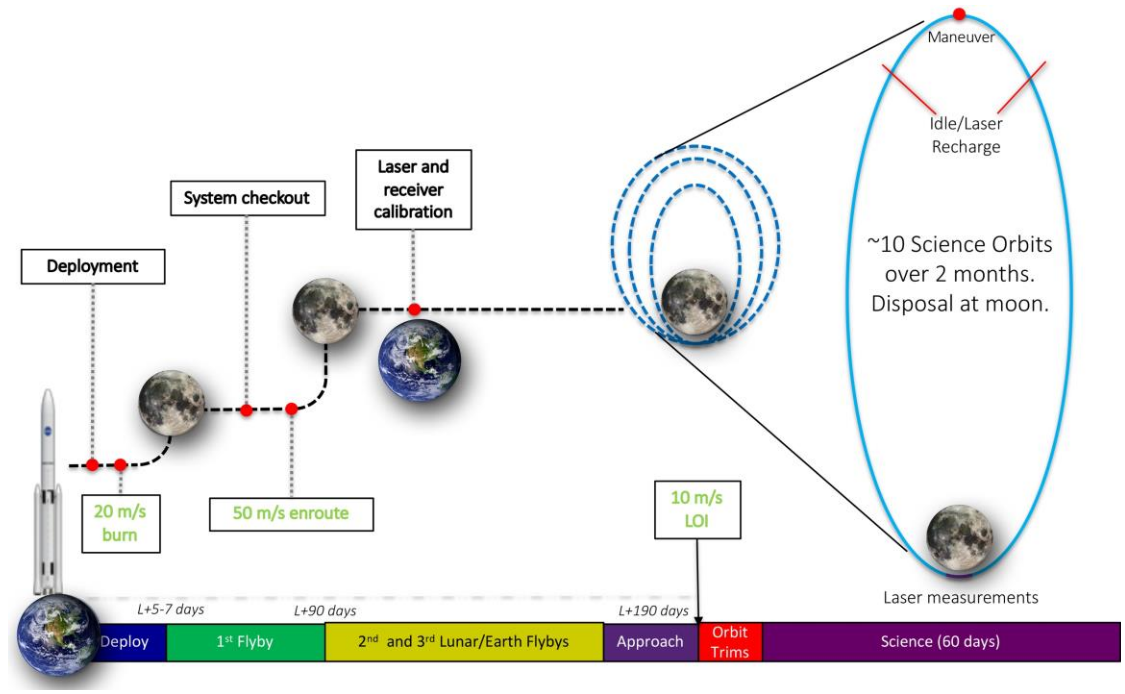

Figure 2. The Lunar Flashlight mission design is amazing and super great.

spacecraft performs three distant Earth and Moon flybys, it will conduct system checkouts, laser power system charge and discharge tests, and instrument calibration (laser test firing and Jupiter observation).

After 190 days, Lunar Flashlight conducts a 10 km/s TCM to insert into a near-rectilinear halo orbit about the Earth-Moon L2 point. The orbit has a 5-7 day polar orbit, a perilune altitude of 15 km, and an apolune of approximately 9000 km. The total delta-V required to achieve the mission is 140 m/s from dispensal, including statistical, gravity loss, and orbit maintenance. The science data collection will take place during 10 orbits over the 2-month planned mission duration, at altitudes of approximately 10 to 50 km within 10° latitude of the lunar south pole. Fuel permitting, it may be able to make more passes; when the fuel is exhausted, the spacecraft will make a controlled crash into the Moon near the south pole.

Spacecraft

Lunar Flashlight uses a standard aluminum CubeSat 6U bus primary structure and weighs approximately 14 kg. Building on the success of the JPL INSPIRE and MarCO satellites [19, 20], Lunar Flashlight uses a single string design with limited fault redundancy and employs COTS components which have been screened for use in space application alongside custom-built subsytems (Fig. 3).

Propulsion: The Lunar Flashlight Propulsion System (LFPS) responsible for placing the spacecraft into a polar orbit around the moon, and performing orbital maintenance throughout its eight-month mission. The LFPS comprises an advanced, low toxicity "green" micropropulsion system (MiPS). The LFPS development is the responsibility of NASA's Marshall Space Flight Center, the MiPS is built by VACCO Industries. The VACCO Lunar Flashlight MiPS is approximately 3U in total volume and uses four 100 mN thrusters to provide a total of 290 m/s of delta-V. The LFPS uses the monopropellant fuel LMP-103S/LT. LMP-103S is an ionic liquid-based blend based on the oxidizer ammonium dinitramide, produced by Eurenco Bofors in Sweden. This propellant has higher specific impulse and higher propellant density than hydrazine, which results in increased performance. The propellant is considerably less toxic, non-carcinogenic and simpler to handle, ship, and store than hydrazine. This propulsion system is a first of its kind, and will mark NASA's first mission using this propellant. The LFIPS uses four 100 mN HPGP Thrusters developed by Bradford ECAPS specifically for use with green propellant. Each thruster

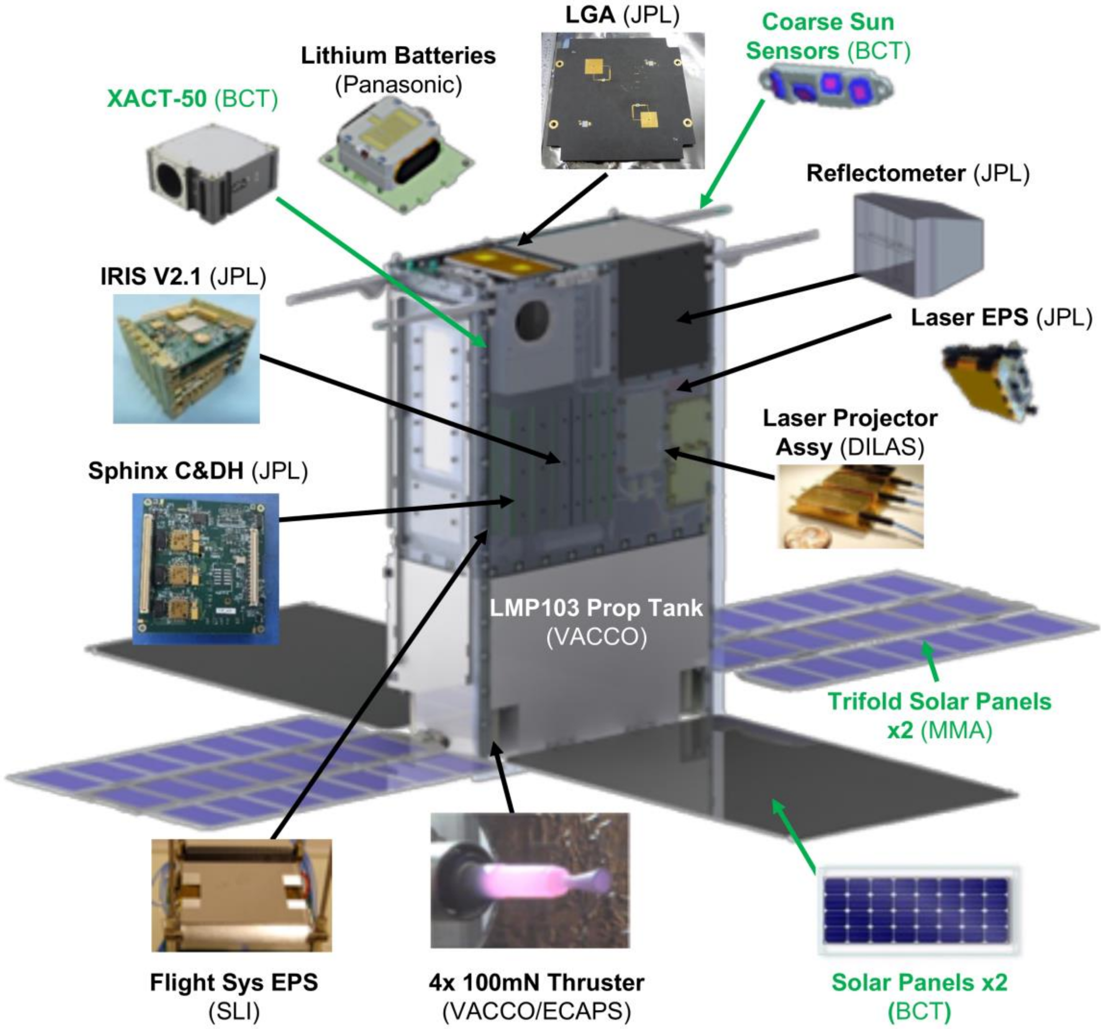

Figure 3. The Lunar Flashlight spacecraft (6U, 14 kg) uses a mix of space-qualified commercial and custom-built components. Components in green were developed through the NASA Small Business Innovation Research program.

independently operates to perform both delta-V and ACS maneuvers controlled by an integrated microprocessor controller.

Power: Lunar Flashlight uses two trifold MMA High Watts per Kilogram (HaWK) deployable solar arrays, two simple 2Ux3U deployable solar arrays, a battery, and an EPS card. Each solar panel has 21 XTJ GaAs cells. The solar panels will provide ~55 W total power at end-of-life. The 6.2 Ah battery contains 3s2p Panasonic NCRB 18650B Li-ion cells. The total capacity of the battery is 48.2Wh at launch day. The battery will be fully discharged by the laser system during each science pass, and recharged over the remainder of the orbit.

Communications: At the planetary distances planned for Lunar Flashlight and other EM-1 missions, they must use X-Band uplink and downlink (7.2 GHz and 8.4 GHz respectively). Lunar Flashlight and other EM-1 missions will use the JPL-developed Iris radio, a radiation-hardened, software defined radio based on other JPL products like the Electra Proximity Radio and the Universal Space Transponder. The Iris radio supports coherent turn-around which allows sequential ranging to be supported, and downlink data rates up to 256 kbps and uplink data rates of 8 kbps. The Iris radio was successfully demonstrated on the MarCO satellites [19]. Lunar Flashlight uses the Iris 2.1 X-Band Transponder with 4 W RF output power, supporting Doppler, ranging, and D-DOR, and two pairs of INSPIRE-heritage low-gain antennas. Uplink commanding and downlink receiving will be conducted using NASA's Deep Space Network.

Command and Data Handling: The C&DH subsystem is a 1U (10 cm x 9.4 cm) single-string architecture composed of a computer board to provide computation, control, storage, and interfacing functions, and an interface board to provide switching, driving, data acquisition, interfacing, and other functions, along with 8GB of rad-hard NAND flash memory. JPL has custom built a radiation-tolerant, miniaturized Sphinx C&DH board. Sphinx uses a dual-core, fault-tolerant LEON3-FT (GR712) processor that can run onboard algorithms for ASA, DTN, and optimal resource planning. The LEON architecture has been proven in space, and the Sphinx board will gain deep-space flight heritage on both the Lunar Flashlight and NEAScout missions.

Attitude control: Attitude control is performed with a Blue Canyon Technologies (BCT) integrated attitude control unit (star tracker, reaction wheels, inertial measurement unit, control algorithms). Lunar Flashlight uses a BCT XACT-50 integrated ACS unit. The XACT-50 is based on the COTS XACT unit, work done on the MarCO mission, and additional work to meet the needs of Lunar Flashlight. The ACS unit receives data from 4 coarse sun sensors and controls the VACCO green propulsion system.

Thermal: Thermal management challenges for the Lunar Flashlight mission include keeping the laser receiver cool while dissipating heat as the lasers fire, the high-temperature propulsion system, and maintaining spacecraft operations in the lunar orbit environment. The Lunar Flashlight thermal design is overall passively cooled and actively heated. The detector operating temperature is maintained at or below -60 °C by a space-facing radiator and isolating the optics from the chassis. Phase-change thermal storage will maintain a constant operational temperature for the lasers during the minutes of operation during the science passes. Both the propulsion unit and the solar panels are thermally isolated from the main spacecraft and the solar panel edges nearest the thrusters are insulated. In addition, four thermostat-controlled heaters will be available.

Flight software: The Lunar Flashlight Flight Software (FSW) subsystem provides on-board spacecraft software functionalities such as commanding, telemetry, uplink, downlink, data storage, time, parameters, data management, fault protection and interface management for various hardware components including the Iris radio, payload, EPS, XACT, propulsion unit, Sphinx and ADCs. Lunar Flashlight FSW is developed using the F Prime framework with heritage from the ASTERIA mission [21].

Summary

Lunar Flashlight is a low-cost cubesat mission to be launched as part of NASA’s first SLS test flight. This innovative mission will demonstrate several firsts, including being one of the first instruments onboard a CubeSat performing science measurements beyond low Earth orbit, and the first planetary mission to use multi-band active reflectometry from orbit. It will demonstrate new 100 mN thrusters using green propellant, providing nearly 25% higher performance than hydrazine in a low toxicity form for transport and storage. Lunar Flashlight will drive infusion of these technologies into smaller satellites and payloads for NASA.

The mission goals are to test new technologies and to detect and map the surface distribution of water ice within the permanently shadowed regions of the lunar south pole. Lunar Flashlight’s four-channel laser projector will illuminate permanently shadowed regions, measuring surface reflectance at wavelengths diagnostic of water ice. Water ice will be distinguished from dry regolith in two ways: 1) spatial variations in albedo, and 2) reflectance ratios between absorption and continuum channels. Water ice band depths will be mapped in order to distinguish the composition of the PSRs from that of the sunlit terrain. These data will be highly complementary to other lunar datasets, including LRO.

Two other missions on the EM-1 launch (Lunar IceCube and LunaH-Map) will make complementary lunar volatile measurements [22, 23]. Although each cubesat uses a different mission design and measurement approach, the results from all three missions will be synergistic when viewed as a fleet of tiny missions simultaneously exploring the nature and distribution of water on the Moon ahead of human exploration.

Acknowledgements

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Biographies

Barbara A. Cohen is the measurement lead for the Lunar Flashlight mission. She is a planetary scientist at NASA Goddard Space Flight Center with scientific interests in geochronology and geochemistry of planetary samples from the Moon, Mars and asteroids. She is a Principal Investigator on multiple NASA research projects, Assistant Project Scientist for the Lunar Reconnaissance Orbiter, a science team member on the Curiosity rover, and leads the Mid-Atlantic Noble Gas Research Laboratory (MNGRL).

Paul O. Hayne is a member of the Lunar Flashlight science team. His research focuses on terrestrial planets and moons, particularly polar ice caps and their interactions with planetary atmospheres. He uses observations from ground-based and spacecraft-based instruments and develops physical models. He is also an active member of several NASA planetary missions.

Benjamin Greenhagen is a member of the Lunar Flashlight science team. He specializes in thermal emission spectroscopy from planetary surfaces and the formation and evolution of their parent bodies. He is the Deputy Principal Investigator of the Diviner Lunar Radiometer onboard the Lunar Reconnaissance Orbiter and helps develop future remote sensing instrumentation. He also runs the Simulated Airless Body Emission Laboratory (SABEL) at APL.

David A. Paige is a member of the Lunar Flashlight science team. He is also the Principal Investigator of the Diviner Lunar Radiometer Experiment on LRO and Deputy Principal Investigator of the RIMFAX Ground Penetrating Radar Experiment on NASA's Mars 2020 Rover Mission.

Calina Seybold is the Deputy Project Manager for Lunar Flashlight. She… [ALSO NEED PIC]

John Baker is the Lunar Flashlight Project Manager. He has nealy 30 years of project and program management experience at JPL and he is an instructor at the California Institute of Technology's Division of Engineering and Applied Science. At JPL, he leads the development of human exploration studies and the development of low-cost robotic exploration systems. He was a program executive at NASA headquarters for the Lunar Reconnaissance Orbiter (LRO) mission, managed the Mars Science Laboratory Project Engineering effort and developed numerous Space Shuttle remote sensing and educational payloads.