

# LUNAR FLASHLIGHT: A 6U CUBESAT USING SOLAR SAIL PROPULSION TO ORBIT THE MOON AND ILLUMINATE PERMANENTLY-SHADOWED REGIONS IN A SEARCH FOR WATER

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**Introduction:** Lunar Flashlight is a 6U CubeSat concept with primary mission to determine whether there is water present, in quantities useful to human exploration, in the permanently-shadowed regions (PSRs) near the lunar south pole [1, 2]. Selected for further study in 2013 by the Advanced Exploration Systems program, Lunar Flashlight would launch on the EM1 mission of NASA's Space Launch System. Shortly after separation from the carrier, Lunar Flashlight would deploy an 80 m<sup>2</sup> solar sail to provide propulsion, spend 8 months and three lunar fly-bys to capture into lunar polar orbit, then another 14 months lowering the perilune to 10–30 km over the lunar south pole. For approximately 60 orbits, the solar sail will be oriented to reflect solar radiation onto the night-side lunar surface (including the PSRs) as the spacecraft passes over the pole, while light reflected back from the lunar surface is collected in a four-channel optical spectrometer on the spacecraft. Water ice, if present at the surface, would be detected in different morphologies and fractional content, and distinguished from other condensed volatiles, by the wavelength-dependent change in surface reflectance.

The Lunar Flashlight program underwent Mission Concept Review/Science Requirements Review during the week of 18 August 2014. In what follows, we describe how the mission would proceed if selected.

**Launch and S/C activities through lunar capture:** The Lunar Flashlight mission begins with ejection from the SLS IPMC. Within the first day, solar panel deployment brings the S/C power-positive. Following a tracking sequence, the primary cold-gas thrust maneuver aligns the S/C for the first of three lunar fly-bys; this expends 30% of the stored propellant, the remainder of which will be used only for momentum-wheel desaturation during the remainder of the mission.

LF employs an ~80 m<sup>2</sup> solar sail as its primary propulsion mechanism; the solar sail and deployment mechanism occupies slightly less than 3U of the 6U CubeSat, and contributes ~2.5 kg to the ~11 kg total mass. The sail is deployed shortly after the first lunar flyby, and over the next 8 months provides vectored thrust to slow the spacecraft and align for capture into lunar polar orbit. Initial lunar orbit altitude is ~9000 km.

**S/C in lunar orbit, spiral-down to Science phase:** Once in lunar orbit, the solar sail continues to provide

vectored thrust to lower the orbit perilune. Approximately 14 months is required to lower the perilune to ~20 km, as required for the science phase. Further constraints on the orbit are that the perilune be in the vicinity of the lunar south pole for science phase (the perilune precesses at about 1.5 degrees of lunar latitude per 13-hour orbit), and that the lunar pole be in darkness for the science phase (the lunar pole has a near-constant 1.53-degree tilt to the ecliptic plane, so experiences 6 months of day, and the same of night, each year). The challenges of navigation with such very-low-thrust propulsion in an environment with significant perturbations from both moon and earth asymmetries should not be underestimated, but will not be detailed further here.

**S/C science phase operation:** The science phase consists of the 60 orbits for which the perilune is less than 30 km and within 10 degrees of the lunar south pole. During passage over the pole, the entire spacecraft is rotated to orient the solar sail 45-degrees to the sunline such that the reflected sunlight illuminates the lunar surface. In this orientation the reflected beam and the spectrometer field-of-view (FOV) will be co-aligned, so that the spectrometer views the illuminated area of the lunar surface and collects light reflected back to the spacecraft. The spacecraft is maintained in this fixed orientation for that part of the orbit within approximately 15 degrees on either side of the pole, where the PSRs are predominantly located. This orientation is indicated in Figure 1.

The spacecraft orbit is essentially inertial, so the moon's rotation results in ground tracks evenly spaced in longitude; 60 orbits yield somewhat more than one full rotation of the moon during Science phase. The mapping is sparse, however, since the ground track width is <2 km wide. Figure 2 is an illustration of representative ground tracks during the science phase.

During Science phase the sail continues to be used to counteract the effects of lunar and earth mass inhomogeneities, but eventually the accumulation of perturbations will result in loss of control, and the S/C will impact the surface.

**Science data interpretation:** Water cold-trapped at the lunar surface would modify the surface spectral reflectance from that of dry regolith. Figure 3 shows the expected spectral reflectance, as a function of water ice content in dry regolith, over the spectral range 1–2

um. The Lunar Flashlight science instrument is a spectrometer with four optical wavelength bands, two in the continuum and two in water-ice spectral absorption bands, as indicated in Figure 3. The optical wavelengths (1.064  $\mu\text{m}$ , 1.5  $\mu\text{m}$ , 1.8  $\mu\text{m}$ , 1.95  $\mu\text{m}$ ) were selected for detection of water ice, comparison to other data (1.064  $\mu\text{m}$  from LOLA), and to optimize detector noise performance in the continuum or absorption bands.

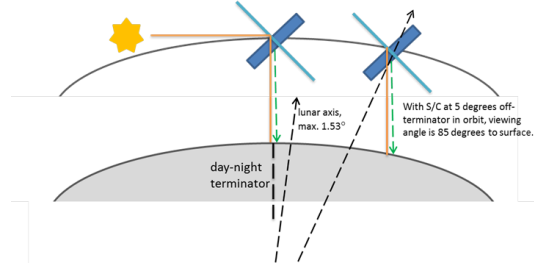


Figure 1. Spacecraft orientation with reflected-light beam co-aligned with instrument FOV during Science pass over lunar south pole.

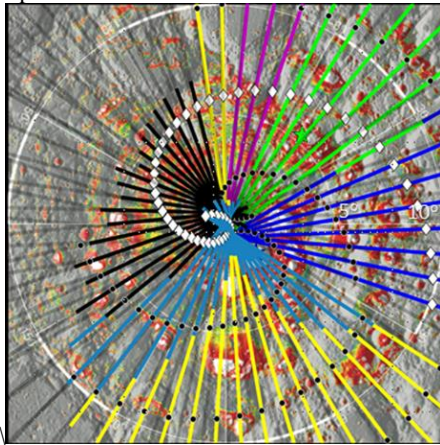


Figure 2. Example of ground tracks over lunar south pole region. White and black dots along the ground track lines are the location of perilune, which precesses during the mission.

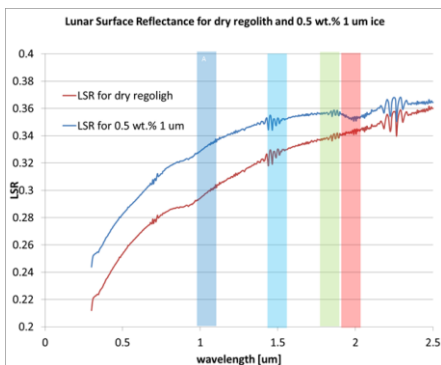


Figure 3. Lunar surface reflectance as a function of wavelength, for dry regolith [3] and for intimate mixture with water ice [4] at 0.5 wt.% content. The colored bands indicate the optical bandpasses of the four spectrometer channels.

The four spectrometer channels view the same ground spot simultaneously. Science data are the ratios of reflected light detected in pairs of spectral channels: comparison of the as-detected ratios with those expected for dry regolith constrains the quantity of water-ice present at the surface. We use the ratio of reflected light in the various bands because the surface illumination is not expected to be known with precision, for a number of engineering reasons.

Figure 4 gives an example of the reflected-light ratio expected in the two shorter-wavelength bands, for one form of water ice, as a function of fractional water content. Having more than two optical channels, thereby probing two separate absorption bands, adds confidence to the detection and potentially enables discrimination of different forms of ice, minerals, and the presence of other condensed volatiles.

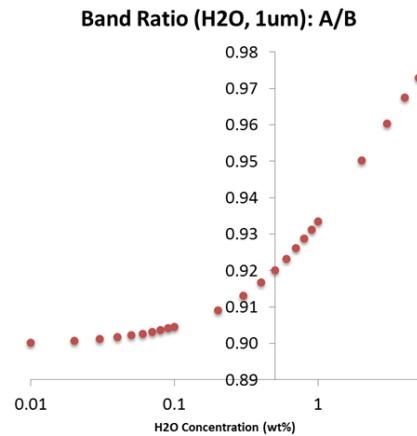


Figure 4. Ratio of reflectance of the two short-wave optical bands as a function of water content.

**Lunar Flashlight spectrometer:** The spectrometer optical package consists of four mirror-symmetric telescopes, each with a flat optical-bandwidth—defining filter in front of an off-axis parabolic (OAP) reflector which directs the light onto a single detector of circular active area. The individual detectors are tilted off-normal to the FOV centerline, to optimize light collection in each individual telescope. All four telescopes view the same scene. The use of OAPs enables locating the four detectors in very close proximity at the center of the four channels, as shown in Figure 5. Co-locating the detectors significantly simplifies cooling and temperature stabilization of the detectors. The optical package incorporates an integral cold finger which extends from the detector block through to the back of the instrument, where it connects to a cryoradiator viewing cold space to cool the detector block to  $<200\text{K}$ .

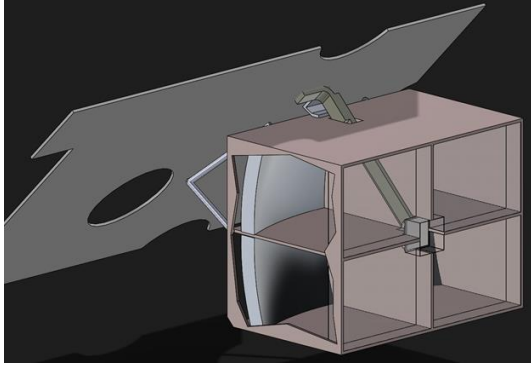


Figure 5. The Lunar Flashlight optical package with integral cold finger and cryoradiator.

The optical detectors are InGa:As single-element photovoltaics, with cutoff wavelength selected for minimum detector noise at each optical wavelength. Devices from Teledyne-Judson [4] are currently baselined, and published data on detector performance is used in performance modeling.

Dedicated instrument electronics operate the Lunar Flashlight spectrometer. The detector current output goes first to a transimpedance amplifier, thence to a voltage amplifier and A—D converter. An FPGA running at several MHz sums a predetermined number of frames for the desired integration time of each observation, which time is presettable via upload and can vary during the data-taking sequence. Additionally the electronics contain current drivers and thermometry readout circuitry for monitoring and control of the detector block and optics housing temperatures. Software running on the FPGA controls the frame co-adding operation and temperature-control activities, and transfers data to and from the spacecraft computer. A “spacecraft simulator” will be developed to run on a commodity computer, for testing of the electronics, software, and integrated spectrometer subsystem.

The entire spectrometer instrument occupies less than 40% of 1U of CubeSat volume: The optical package is 5 cm x 6 cm x 8 cm, and the electronics package is expected to be smaller than 2 cm x 9 cm x 9 cm. The cryoradiator occupies most of one 1U x 2U face of this 6U CubeSat, but is only 0.5 cm thick. Power draw is expected to be less than 0.5 W. The total mass is not yet well-defined, but will probably be less than 350 g.

We have developed a performance model for the instrument which includes temperature-dependent detector noise, thermal noise sources, realistic electronics performance, and preliminary optical throughput for the current design. One output of the model is the signal-to-noise ratio (SNR) in each optical band, which for any variation in reflectance versus water content (as per Figure 4) immediately gives the detection capabil-

ity, phrased as N-sigma confidence of detection, for that water content.

A critical component of this approach is, of course, obtaining sufficient illumination of the lunar surface via reflection of the sun from the solar sail. This functionality is currently being developed at MSFC [5]. Our modeling indicates that, with only 3% of the sunlight incident on the solar sail reflected onto the lunar surface within the spectrometer, we have the capability to discriminate surface water ice present at 0.005 weight fraction from dry regolith at the 3-sigma confidence level in both the short-wavelength and long-wavelength spectral band ratios, from an altitude of 20 km above the lunar surface, with spatial resolution of 1 km. This is a very robust detection capability which will easily satisfy the Lunar Flashlight mission requirements.

**Summary:** The Lunar Flashlight mission concept addresses strategic knowledge gaps for NASA’s HEOMD through novel or unique technology applications. Achieving lunar orbit with a solar sail, and using a remote source for active spectroscopy of permanently-shadowed regions would be, to our knowledge, unprecedented. The expected detection capability for water ice at engineering-usable levels is robust and flexible. Further, this design of the spectrometer optical and electronic system could easily be modified for similar CubeSat-scale missions.

#### References:

- [1] Hayne P. O. et al. (2013) *LEAG*, Abstract #1748.
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