Lunar Flashlight Science Ground and Flight Measurements and Operations Using a Multi-band Laser Reflectometer

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# ABSTRACT

The Lunar Flashlight cubesat mission was designed and flown to collect new data on the abundance and distribution of water ice frost in lunar permanently shadowed regions (PSRs) using active laser spectroscopy. Key advantages of active spectroscopy are that it can collect surface reflectance data in locations and conditions where passive spectroscopy cannot operate, specifically nightside locations where no indirect lighting is available, and in the deepest parts of PSRs where indirect lighting may be too faint for passive spectroscopy. Lunar Flashlight launched in 2022 but because of a propulsion system failure, did not make it to the Moon to conduct its science investigation. However, Lunar Flashlight proved to be an extremely successful technology demonstration mission, meeting or exceeding all its technology-focused mission goals, including demonstrating its instrument functionality. This paper describes the extensive ground and test campaigns to characterize the Lunar Flashlight laser reflectometer instrument and its planned utility for science observations, along with recommendations for future instrument design, development, verification, and use.

# 1. INTRODUCTION

Lunar permanently shadowed regions (PSRs) are of wide interest to both science and human exploration because of their potential to harbor species that may be used to sustain exploration activities. The slight tilt of the lunar spin axis (1.54°) relative to the ecliptic plane causes solar illumination to fall at a grazing angle to the surface in polar regions, and results in many polar craters and topographic depressions being unilluminated throughout the year ([Urey, 1952](#_ENREF_53); [Watson et al., 1961](#_ENREF_55)). In these PSRs, the lack of direct sunlight coupled with the low internal heat flow of the Moon measured by Apollo surface experiments ([Nagihara et al., 2018](#_ENREF_33)) results in surface temperatures as low as 40K ([Paige et al., 2010](#_ENREF_37); [Williams et al., 2019](#_ENREF_56)). These environmental conditions mean that the PSRs may be “cold traps,” or regions where volatile species could be stable at the surface or near surface because the maximum surface temperature is below the sublimation temperature of many volatile elements and compounds ([Zhang and Paige, 2009](#_ENREF_57)).

Condensed volatile species (*e.g.,* ices) are widely thought to occur in the subsurface and surface regolith in many of these lunar polar cold traps. Both Earth- and lunar orbiter-based radar and neutron spectrometer measurements indicate the presence of subsurface water ice at the lunar poles; if water ice were confined to PSRs alone, this would correspond to about 0.5 wt.% in the south polar PSRs ([Campbell et al., 2003](#_ENREF_4); [Feldman et al., 2001](#_ENREF_15); [Mitrofanov et al., 2016](#_ENREF_32); [Nozette et al., 2001](#_ENREF_35); [Sanin et al., 2012](#_ENREF_42)). The LCROSS mission excavated material from tens of meters of depth in the permanently-shadowed interior of the Cabeus crater, one of the most hydrogen-rich regions of the south pole. The LCROSS spectrometers observed ejected regolith with 5-10 wt.% water, along with other volatile substances, including ammonia and simple carbon compounds ([Colaprete et al., 2010](#_ENREF_11); [Heldmann et al., 2012](#_ENREF_21)). Surface volatiles (e.g., water frost) have also been detected from orbit within some PSRs, though their distribution is “patchy” rather than contiguous over regions with similar thermal environments ([Fisher et al., 2017](#_ENREF_16); [Hayne et al., 2015](#_ENREF_19); [Lemelin et al., 2014](#_ENREF_26); [Li et al., 2018](#_ENREF_28)).

Water ice and other condensed species are critical components of many In-Situ Resource Utilization (ISRU) paths envisioned by NASA and the space community (*e.g.,* ([Anand et al., 2012](#_ENREF_2); [Duke et al., 2006](#_ENREF_14); [NASA, 2020](#_ENREF_34); [Sanders, 2018](#_ENREF_41); [Siegfried and Santa, 2000](#_ENREF_43)). Simple identification of the presence of water is not adequate for ISRU architecture planning and engineering design; rather knowledge that the resource is extractable and can be done so economically and legally is critical ([Cannon and Britt, 2020](#_ENREF_5); [Kleinhenz et al., 2020](#_ENREF_25); [United States Geological Survey, 1980](#_ENREF_52)). Understanding the composition, quantity, distribution, and form of water and other volatiles associated with lunar PSRs is therefore carried as a NASA Strategic Knowledge Gap (SKG) ([Lunar Exploration Analysis Group Specific Action Team (SAT), 2011](#_ENREF_30)). Observations of surface frost and subsurface hydrogen abundance can be used to model the locations and mass of water ice deposits, but billions of years of geologic activity on the lunar surface, principally impact gardening, have likely disrupted the initial distribution and created the patchy distribution observed today ([Brown et al., 2022](#_ENREF_3); [Cannon et al., 2020](#_ENREF_6); [Tai Udovicic et al., 2023](#_ENREF_51)). Direct observations of the surface distribution of water ice in PSRs would improve constraints on the modeled distribution and abundance of water, which in turn would help further ISRU campaigns.

The Lunar Flashlight (LF) mission was designed and flown to collect new data on the abundance and distribution of water ice frost in PSRs to address this Strategic Knowledge Gap. Lunar Flashlight was selected in 2014 by the NASA Advanced Exploration Systems (AES) program within the Human Exploration and Operations Mission Directorate (HEOMD) in partnership with the Space Launch System (SLS) for launch as an Artemis I secondary payload. This arrangement imposed specific limitations on size, mass, propellant type, safety, etc. that were carried throughout the Lunar Flashlight development cycle. In 2017, Lunar Flashlight was incorporated into NASA’s Space Technology Mission Directorate (STMD) portfolio as a technology demonstration mission with a science focus. The Lunar Flashlight mission requirements were set to be commensurate with its mission classification, with one Level 1 requirement to *demonstrate the ability* to detect and map surface water ice in lunar PSRs and one Level 1 requirement supporting successful demonstration of key technologies in communications, propulsion, C&DH, and mission operations (Table 1).

Table 1. Lunar Flashlight Level 1 Mission Requirements

|  |  |  |
| --- | --- | --- |
| **Level 1 Mission Requirement** | **Level 2 Design Requirement** | **Rationale** |
| **L1-01: Address SKG**  Lunar Flashlight shall have the capability to address a key strategic knowledge gap at the Moon.  ***Full Success Criteria****:* Detect and map surface water ice on the Moon with a spatial resolution of 1 km over 10% of the permanently shadowed and occasionally sunlit regions poleward of 80°S latitude.  ***Minimum Success Criteria****:* Demonstrate the ability to detect surface water ice content with a spatial resolution of 10 km or better with multiple measurements in permanently shadowed and occasionally sunlit regions poleward of 80°S latitude. | **L2-13: Measure Water Ice:** The project shall measure the abundance of exposed lunar volatiles in the lunar regolith with a minimum abundance of 2 wt.%. | This requirement addresses the need to fill Strategic Knowledge Gaps (SKGs) to understand the composition, quantity, distribution, and form of water and other volatiles associated with lunar cold traps. |
| **L2-14: Ice Distribution Mapping:** Measure the abundance of water ice frost in a 10 km area of two permanently-shadowed regions (PSRs) and one non-PSR location within 10° of the lunar south pole. |
| **L1-02: Form Factor**  Lunar Flashlight shall be in a 6U cubesat form factor compatible with a NASA provided cubesat deployer for launch on a NASA provided launch vehicle. | Multiple, including:   * Mission Duration * Planetary Protection * Data Communication * Mission Disposal * Launch Vehicle Interface Control * Orbit and Trajectory * Data Downlink | This requirement addresses the need to demonstrate low-cost reconnaissance capability for HEOMD through the use of innovative solutions. |

Though Lunar Flashlight was not a science mission and as such, did not carry science requirements, Lunar Flashlight set a measurement (or science) goal to detect and map surface water ice over 10% of the permanently shadowed and occasionally sunlit regions poleward of 80°S latitude, with a minimum success criterion to demonstrate such a capability. The surface area occupied by water ice cold traps on the Moon is ~105 km2, predominantly poleward of ~80°S, more-or-less evenly distributed in longitude ([Mazarico et al., 2011](#_ENREF_31)). The mission measurement goal was to measure the abundance of exposed lunar volatiles in the lunar regolith with a minimum abundance of 2 wt.%; this requirement was designed to encompass the “operationally useful” concentration of ice ([Kleinhenz et al., 2020](#_ENREF_25); [Sanders, 2018](#_ENREF_41)). The spatial resolution of 1 km for Lunar Flashlight was intended to make multiple along-track measurements within the largest (~20km) PSR and to enable future surface assets to target specific areas ([Heldmann et al., 2016](#_ENREF_20); [Speyerer et al., 2016](#_ENREF_48)). Though Lunar Flashlight would only be able to make these measurements in a limited number of surface passes, these measurements were intended to enable prediction of other ice deposits by correlating data with other mapped geologic characteristics and environments, including latitude, temperature, topography, and lighting conditions.

Meeting the measurement goal required Lunar Flashlight to develop a payload capable of detection of surface frost by the spacecraft in PSRs. The most diagnostic, unambiguous way to remotely sense water ice would be by infrared spectroscopy, with a water ice fundamental absorption at 3 mm, and overtones at 2 mm and 1.5 mm ([Clark et al., 2014](#_ENREF_9)). This experiment required active illumination to detect surface ice, if present, under any illumination conditions, including the darkest parts of PSRs where very few solar photons are available for spectroscopy. As originally envisioned and proposed, the Lunar Flashlight design would have used a solar sail for both propulsion and illumination, reflecting sunlight off an 80m2 mylar sail onto the lunar surface ([Johnson et al., 2015](#_ENREF_24)). However, further analysis showed that the 14-kg spacecraft could not be adequately maneuvered into lunar orbit using a solar sail, so the Lunar Flashlight project changed its technical approach, moving to a chemical propellant and to an active illumination source for measurement. After considering several alternatives (inflatables, smaller deployables, flashlamps, pumped lasers, etc.) and constrained to the very small volume available to the payload, the team baselined a stacked-bar diode laser design based on commercially-available parts to provide illumination.

The final design and ground- and space-based testing for the Lunar Flashlight payload is described in this paper. Table 2 provides an overview of the major payload parameters, discussed in this paper and in ([Vinckier et al., 2019](#_ENREF_54)). The Lunar Flashlight illumination system uses stacked laser diode bars to emit short (few ms) energy pulses in rapid sequence at four near-IR wavelengths diagnostic of water ice (two in absorption bands and two in continuum bands), while a receiver system detects the reflected light. Derived reflectance and water ice band depths would be mapped onto the lunar surface to identify locations where H2O ice is present. Individual measurements would be expected to have a surface footprint of ~100-200 m at spacecraft altitudes of 10-20 km; measurements were planned to be added along-track to increase the SNR, resulting in an along-track mapping resolution of a few km. The total duration of laser firing per pass would be approximately 2-3 minutes during closest approach over the south pole, including multiple PSRs and potentially other areas of interest such as landing sites for Commercial Lunar Payload Services (CLPS) landers, Artemis III landing sites, and international missions. More information on other aspects of the Lunar Flashlight spacecraft and mission can be found in these references: ([Cheek et al., 2021](#_ENREF_7); [Cohen et al., 2020](#_ENREF_10); [Hauge et al., 2023](#_ENREF_18); [Huggins et al., 2021](#_ENREF_22); [Rizvi et al., 2022](#_ENREF_39); [Ryan and Foor, 2021](#_ENREF_40); [Smith et al., 2021](#_ENREF_44); [Smith et al., 2023](#_ENREF_45); [Starr, 2023](#_ENREF_49); [Sternberg et al., 2022](#_ENREF_50)).

Table 2. Overview of the Lunar Flashlight payload parameters discussed in this paper and in ([Vinckier et al., 2019](#_ENREF_54))

|  |  |
| --- | --- |
| Laser technology | Stacked diode bars (Dilas Coherent, Inc) |
| Passbands of the lasers | 1064, 1530, 1850, 1990 nm |
| Laser unit dimensions | ~9.6 × 6.2 × 4.18 cm; ≤750 g |
| Optical Power | 14-35W at 2.8 V and 45A |
| Pulse Width | 1 ms |
| Frequency | 200 Hz |
| Beam profile | ≤17 mrad Residual Divergence |
| Detector technology | 2.4-µm cutoff InGaAs (Teledyne Judson) with a 2-mm diameter detector |
| Receiver dimensions | ~80 × 80 × 95 mm |
| Receiver aperture | ~75 × 75 mm |
| Mirror focal length | 70 mm |
| IFOV of the receiver spot | 20 mrad |
| noise equivalent power of the detector at 2.06 µm, 208 K, 1 kHz, and 0V bias (manufacturer spec) | 9.3E-14 W/ Hz max, 6.6E-14 W/ Hz typical |

# 2. PAYLOAD DESIGN

Laser altimeters measure laser pulse time of flight to determine the range to the surface, pulse spreading caused by surface roughness, and the ratio of transmitted to returned energy, which is related to the surface reflectance. Typical planetary laser altimeters use diode-pumped laser sources to emit photons, which strike and are backscattered from the lunar surface ([Cremons, 2022](#_ENREF_12); [Hussmann, 2014](#_ENREF_23)). Because of the lidar geometry, these surface reflectance measurements are always collected at zero phase, which obviates the need for (empirical) photometric corrections to relate observations taken at different times or locations. Such active reflectance measurements can also be made over unilluminated surfaces, where the lidar source provides the incident light. For example, the LOLA measurements have been important to the study of the distribution and origin of lunar polar volatiles (*e.g.,* ([Fisher et al., 2017](#_ENREF_16); [Lemelin et al., 2016](#_ENREF_27); [Qiao et al., 2019](#_ENREF_38)).

The Lunar Flashlight (hereafter, LF) instrument uses active laser illumination, but its design and implementation had to meet the size, mass, power, and thermal constraints of the 6U CubeSat form factor and thus does not include the ranging capacity of a true lidar system. Rather, the Lunar Flashlight payload is an active reflectometer employing a compact high power diode laser which emits an IR beam at optical power up to 72W. The laser electrical power system (L-EPS) takes advantage of compact lithium ion (Li-ion) battery technology to provide the energy needed to drive the laser and dissipate the thermal load of the power electronics in a small volume. In addition, instrument electronics were developed to occupy a compact package but with the ability to be tuned to deliver the high performance required of this instrument.

## 2.1 Overview

The LF instrument was the only payload on the spacecraft (Fig. 1), occupying 2U of the 6U spacecraft. The LF payload is a multi-band reflectometer based on an optical receiver that is aligned with four diode laser stacks, each emitting in a different near-infrared wavelength. The instrument is built on a sideplate that supports the optical receiver and the laser emitter in a very precise and stiff mechanical structure. The receiver comprises a 70 mm off-axis parabolic mirror (OAP) and a baffle assembly to shield the InGaAs detector from stray light. The detector is cooled by an aluminum radiator which is mounted on the receiver body and radiates to deep space. The Laser and L-EPS are mounted on a box containing phase-change material (PCM) for thermal dissipation. The instrument main electronics, the Digital (DPLE) and Analog (APLE) Payload Electronics boards, are mounted to the CubeSat frame. Three Li-ion 18650 battery cells, separate from the spacecraft battery cells, are mounted to the midplate to provide power for the lasers.

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Figure 1. a) the assembled Lunar Flashlight spacecraft (with B. Cohen and N. Cheek for scale); b) view of the spacecraft model showing the location and volume of the payload module; c) Lunar Flashlight payload components.

In nominal operation (Fig. 2a), the LF lasers would fire sequentially for 6 ms each, followed by a pause of 6 ms with all lasers off. The optical receiver would collect and measure the light reflected from the lunar surface field of view (FOV), which is 20 mrad. A measurement with all lasers off quantifies the background, which is the sum of detector dark current, thermal emission from the receiver incident on the science detector, and solar illumination and Earthshine reflected from the lunar surface (both inside and outside its FOV). This background measurement would be offset from each laser light measurement (discussed further in Section 2.4). The strength of a water ice absorption feature would be determined by taking the ratio of each band measurement to the adjacent continuum measurement.

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Figure 2. a) Lunar Flashlight concept of measurement (not to scale). Each laser fires in sequence as the spacecraft travels along track. The intensity at the receiver would be distinguished by the time of receipt, with the blank used to determine the background. b) Infrared spectra showing that water ice (pale blue line) has two prominent molecular absorption features at ~1.5 and ~2 micrometers, whereas dry lunar regolith (black line) has a largely featureless spectrum and an increasing albedo with wavelength (red slope); mixtures of ice and regolith are also shown for comparison. The Lunar Flashlight laser wavelengths are shown as colored bars, chosen in pairs to observe each ice absorption feature and a nearby continuum point.

LF laser wavelengths were optimized to distinguish water ice absorption bands from dry lunar regolith using two pairs of molecular water absorption bands and continuum measurements (Fig. 2b). The selected central wavelengths (and requirements) are 1.064 (-0.060 / + 0.230) µm & 1.850 (-0.030 / +0.020) µm for continuum measurements and 1.530 (-0.015 / +0.015) µm & 1.990 (-0.020 / +0.025) µm for absorption bands. We shifted the short-wavelength water absorption from its nominal position at 1.495 to better match the results from ([Li et al., 2018](#_ENREF_28)), where observed water ice detections had absorption minima shifted ∼0.05 μm to longer wavelengths compared with those of pure ice frost in terrestrial experiments. The Lunar Flashlight 1.064 µm laser is functionally the same wavelength used by the Lunar Orbiter Laser Altimeter (LOLA) instrument on LRO ([Smith et al., 2009](#_ENREF_46)), potentially enabling a tie point of absolute surface reflectance, though at different spatial scales.

Consistent with the budget constraints and risk tolerance of the Lunar Flashlight project, the payload followed a “proto-flight” (PF) model philosophy for the instrument in that environmental and functional tests were performed on the flight model (FM) optics and receiver hardware, although at reduced levels. The laser unit followed a more traditional philosophy, where an engineering model (EM) underwent multiple alignment and vibration tests that drove out issues prior to the FM build. All payload electronics were PF and developed without an EM, although there was a “breadboard” developed for the laser electronics.

## 2.2 Laser Unit

The LF laser assembly consists of four diode bar packages developed by Dilas Coherent Inc, associated laser electronics, and the thermal control phase change material (PCM). 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). Each laser diode package emits at a different infrared wavelength with its own collimation lens, and all are aligned to the LF receiver FOV.

The four diode packages are arranged in a square configuration adjacent to the LF receiver aperture (Fig. 1c). The laser modules and associated laser electronics are attached to a copper heatsink, which in turn is bolted to a chassis containing the PCM. The PCM dissipates heat from the lasers and laser electronics over the experiment duration, while the PCM enclosure acts as the mechanical interface between the laser assembly and the receiver assembly. To ensure boresight between the laser and receiver assemblies, six titanium alloy flexures connect the PCM chassis to the receiver assembly. Two of the six flexures have fine tip/tilt adjustments that were used to achieve sub-mrad pointing adjustment of the laser assembly during spacecraft integration. Final alignment of the laser and receiver assemblies was performed by scanning the laser pointing across the receiver FOV in the horizontal and vertical axes and pinning the tip/tilt adjustments to halfway between the edges of the FOV. Dilas Coherent Inc. performed measurements of the laser far-field patterns and spectral profiles as a function of laser temperature for each of the four flight lasers. Far-field laser profiles (Fig. 3) were measured by focusing the laser output onto a sensitive InGaAs camera using a 160 mm focal length lens. The angular deviation of the beam profile was then determined based on the camera pixel dimensions and focal length of the lens.

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Figure 3. Measured angular far-field beam profiles for the four flight laser modules, a) 1064 nm, b) 1530 nm, c) 1850 nm, and d) 1990 nm. The color scale denotes each laser’s radiance normalized by its maximum value. The black circles illustrate the nominal LF receiver FOV. The zero points on each axis correspond to the centroid of the average of all four beam profiles, thus the co-alignment of the four lasers is also shown here.

Converting the LF normal albedo measurements into water ice abundance requires knowledge of the laser spectral profile (center wavelength and linewidth) to feed into spectral retrievals. In contrast to planetary lidars such as the Lunar Orbiter Laser Altimeter (LOLA), which operates at a nearly constant 1064.4 nm ([Smith et al., 2010](#_ENREF_47)), the diode laser technology used for LF results in a broader laser linewidth between 2.5 and 14 nm. Figure 4 shows the measured spectral profiles of the four lasers at 20 °C and 45 A. The laser wavelengths also shift as a function of laser temperature and drive current due to the combined effects of changes in the index of refraction of the gain medium and a shift of the gain profile itself ([Demtröder, 2014](#_ENREF_13)). During a nominal 90 second experiment, the laser temperature is expected to vary between 17 and 26 °C based on system-level cryo-vacuum test results. Simultaneous temperature and drive current tuning rates of the four lasers were characterized by measuring the spectral profiles of the lasers while they were tuned over a grid of temperatures (17 to 23 °C in 1 °C steps) and current (40 to 45 A in 1 A steps). A Gaussian profile was then fit to each measured laser spectrum using a non-linear least-squares regression, yielding a center wavelength and linewidth (full-width at half-maximum, FWHM). Measured wavelength and drive current tuning rates are shown in Figure 5. No significant changes in the spectral profile shapes or linewidths were observed over the tested temperature and current range.

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Figure 4. Measured spectral profiles (black lines) and Gaussian fits (red lines) for the four flight laser modules at 20 °C and 45 A, a) 1064 nm, b) 1530 nm, c) 1850 nm, and d) 1990 nm. The spectra here were normalized by the amplitude of the fit Gaussian curve.

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Each laser’s output power also depends simultaneously on the drive current and temperature. Because laser power is not directly measured within the payload, it must be inferred from the laser module’s measured temperature and current. This relationship was characterized during subsystem testing by measuring each laser’s integrated power over a grid of drive currents (40 to 45 A in 0.1 A steps) and temperatures (17 to 23 °C in 1 °C steps) (Figure 6). These data were fit with a multi-linear regression yielding the nominal laser output power, temperature tuning rate, and efficiency (Table 3).

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Figure 6. Measured laser output power over a grid of drive currents and temperatures for each of the four flight laser modules. The data for each laser is fit with a multi-linear regression and the corresponding residuals are shown in each lower plot.

Table 3. Laser parameters derived from flight model ground characterization.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Wavelength Band (nm) | 1064 | 1530 | 1850 | 1990 |
| Linewidth (FWHM) (nm) | 2.5 | 14 | 8 | 11 |
| Centroid Wavelength @ 45A, 20℃ (nm) | 1058.5 | 1533 | 1844 | 1985 |
| Centroid Wavelength Tuning Rate (nm/°C) | 0.239 | 0.801 | 1.056 | 1.107 |
| Centroid Wavelength Current Dependence (nm/A) | 0.034 | 0.485 | 0.735 | 0.854 |
| Output Power @ 45A, 20℃ (W) | 71.620 | 26.019 | 15.645 | 14.073 |
| Power Tuning Rate (W/°C) | -0.140 | -0.256 | -0.136 | -0.078 |
| Power Efficiency (W/A) | 1.928 | 0.737 | 0.386 | 0.326 |

## 2.3 Receiver

The Lunar Flashlight receiver uses a 70 × 70-mm, aluminum, off-axis paraboloidal mirror with a focal length of 70 mm, which collects the reflected light from the Moon surface onto a single-pixel InGaAs detector with a 2-mm diameter, providing a 20-mrad field of view. The detailed optical, mechanical, and thermal design of the receiver can be found in ([Vinckier et al., 2019](#_ENREF_54)).

We present here the spectral responsivity of the LF detector over a range of wavelengths for each of the four LF laser channels as measured using the setup described in ([Vinckier et al., 2019](#_ENREF_54)). Note that the reference’s detector temperature of 208 K refers to the temperature setpoint of the ground support equipment Lakeshore PID system. At this setpoint temperature, the flight electronics read -61°C, the in-flight operational temperature of the detector. After publication of Vinckier et al. (2019), the 1495 nm laser diode was changed to a 1530 nm laser diode to align with results from ([Li et al., 2018](#_ENREF_28)). Also, as shown in the previous section, the wavelength of each laser may change depending on the drive current and temperature. Therefore, the responsivity of the detector at -61°C was measured over numerous wavelengths surrounding each laser module’s nominal wavelength (Fig. 7). The responsivity measurements for each channel were also fit with a linear regression. The updated responsivity measurements at the nominal laser wavelengths, as well as the associated wavelength dependences, are shown in Table 4. The 2-sigma uncertainty in the absolute responsivity measurements is ±5% due to systematic uncertainty in the calibration equipment. The 2-sigma uncertainty in the relative responsivity between each channel is only ±1.5%. The LF mission planned to execute a cross-calibration with the LOLA lunar surface reflectance measurements (which themselves were scaled to Kaguya Multiband Imager zero phase measurements ([Lemelin et al., 2016](#_ENREF_27); [Smith et al., 2010](#_ENREF_47))) during science operations to better calibrate the detector’s absolute responsivity for the 1064 nm band. By comparing initial LF reflectance measurements to those taken by LOLA’s 1064.4 nm band, the absolute calibration of the LF 1064 nm band could be improved and the corresponding responsivity of all four bands updated.

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The spectral responsivity of the LF detector has a small dependence on its temperature. Using the same setup that measured the absolute responsivity, the detector current was measured as the detector temperature varied from -66 °C to -56 °C (according to the flight software) in 2 °C increments for three wavelengths per LF laser channel. These measurements are represented in Figure 8 as the relative change in detector responsivity from the average of the -62 °C and -60 °C responsivity measurements. The slope of the line fit to the measurements made at the wavelength closest to that of each laser channel (1055 nm, 1530 nm, 1843 nm, and 1985 nm) converted to A/W per °C is shown in Table 3. The wavelength dependence in slope is negligible within the expected wavelength range for each channel. The LF detector is controlled to -61 ± 0.5°C to minimize these temperature effects on the measured current, and the resultant 0.11% change in responsivity for the 1064 nm band is well below any science uncertainty requirements. However, the authors note that during end-to-end testing there was still a noticeable systematic effect on the measured current that strongly correlated with the detector temperature. This effect was nearly completely mitigated by introducing this responsivity correction to the instrument model (see Section 2.4).

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Figure 8. Measured change in responsivity over a range of detector temperatures for each of three wavelengths per LF laser wavelength band. The displayed detector temperature is that reported by flight software.

Table 4. Detector parameters derived from flight model ground characterization.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Wavelength Band (nm) | 1064 | 1530 | 1850 | 1990 |
| Responsivity  (±5% abs., ±1.5% rel.)  @ -61°C (A/W) | 0.338  @ 1064 nm | 0.852  @ 1530 nm | 1.034  @ 1850 nm | 1.106  @ 1990 nm |
| Responsivity Wavelength Dependence (A/W) / nm | 0.750e-3  (0.22%) | 1.368e-3  (0.16%) | 0.493e-3  (0.05%) | 0.384e-3  (0.04%) |
| Responsivity Temperature Dependence (A/W) / °C | 0.358e-3  (0.11%)  @ 1055 nm | -0.271e-3  (-0.03%)  @ 1530 nm | 0.153e-3  (0.015%)  @ 1843 nm | 0.263e-3  (0.02%)  @ 1985 nm |

## 2.4 Integrated Instrument model

The LF instrument model is based on the characterization and calibration results described in this section and forms a data processing pipeline that converts the raw LF data into measured radiometric quantities for further analysis. The instrument model processing stages are shown schematically in Figure 9.

Diagram, timeline

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Figure 9. Lunar Flashlight instrument model block diagram. The white rectangles denote processing steps and the major data product levels (L1a, L1b, L2) are represented as colored boxes. Colored rectangles correspond to LF science data (green) as well as data sources outside the raw science data including ground and cruise-phase calibration/test data (gray), instrument design values (brown), SPICE/ephemeris data (gold), and S/C telemetry data (blue).

A brief description of the LF instrument model is given here. The raw science data is first converted from binary format to engineering units. The most critical LF science data product is the detector current values on which the received signal is based. All LF raw data is recorded within the payload at a frequency of 23.7 kHz. The relevant measured quantities (with associated units) that act as inputs to the instrument model are: Timestamp (μs); Laser ID; Detector Current (nA); Detector Temperature (°C); Laser Current (A); and Laser Temperature (°C). The nominal LF experiment involves firing the four lasers sequentially, with a blank period (no laser fired) at the end. Each laser is fired in a “pulse” which is nominally 6 ms in duration, the collection of all four laser pulses and the blank period is a 30-ms “frame”, and two frames together form a 60-ms “sequence” which is the level at which the payload command string is created. The instrument timestamp is reset at the beginning of each experiment and is translated to UTC using the spacecraft command telemetry. Detector current quantities measured from a single pulse sequence, with associated timing references and definitions, are shown in Figure 10.

Chart, line chart

Description automatically generated

Figure 10. Timing reference and definitions for LF raw detector current data. Data sequences comprise two frames. Each frame comprises five pulses. In this example from ground testing, the order was 1530 nm (blue), 1064 nm (orange), 1850 nm (green), 1990 nm (red), blank (purple).

The time-tagged detector current values are the primary science product from which the normal albedos are eventually derived. These time-tagged detector current values are first sectioned based on which laser was firing at each timestamp. This results in segments of 142 or 143 data points for each laser pulse. Because the detector current is digitized much faster than the detector electronics bandwidth, there is a “transient period” at the transition between each laser firing. This transient period also includes thermal and electrical transients in the laser and laser electronics which lead to unstable laser power. This transient period of 40 samples (1.7 ms) is removed from the beginning of each laser pulse, and only the following 100 samples (4.2 ms) are used for further processing. The final two or three samples are also considered transient and are removed. The mean current value from each 100-sample section is reported as the laser channel detector current for each frame. The measurement noise is estimated by fitting a line to this 100-sample section and calculating the standard error of the mean on the residuals of this fit.

No direct measurement of the laser optical power and centroid wavelength exists onboard LF, so they must be estimated from the measured laser temperature and drive current using the parameters derived in Section 2.2. Similarly, the detector responsivity is estimated based on its temperature as in Section 2.3. The laser temperature, laser current, and detector temperature are all recorded at the same rate as the science data (23.7 kHz). Each frame is assigned a single laser temperature, laser current, and detector temperature by taking an average value of all samples in which a laser is firing during the frame (*i.e.,* omitting the blank pulse). As seen in ETE testing (Section 2.5), the drive current drops to 0 A, the measured temperature drops by as much as 1°C, and the detector temperature drops by as much as 0.5°C during the blank pulse, therefore these samples are omitted from the average. A median is used over a mean for the laser temperature and current values to mitigate the effect of single-sample transients.

Each frame is assigned the timestamp of the first sample within the frame. The collation of frame-wise timestamp, detector current for each laser channel (x5), laser temperature, laser current, and detector temperature make up the Level 1A (processed) LF data product.

On a frame-by-frame basis, the laser wavelength , laser output power , detector responsivity , and detected laser power are all calculated for each laser channel using the measured quantities and characterization parameters:

,

,

,

.

Note that the detector current measured during the blank laser pulse is subtracted when calculating the detected power for each laser channel. These calibrated measurements make up the Level 1b (calibrated) LF data product.

Finally, the Level 1b data would be combined with instrument pointing and spacecraft telemetry (spacecraft position and attitude with respect to a lunar surface model) to determine the latitude and longitude of the laser footprint and the range to the surface for each laser frame. The 30-ms duration of each frame corresponds to roughly 60 meters of along-track motion, well within the 200+ meter footprint, such that the four pulses within each frame can be considered to be from the same location. The normal albedo for each laser channel at each frame location (the Level 2 LF data product) is estimated using the laser altimeter link equation ([Abshire et al., 2000](#_ENREF_1); [Gardner, 1982](#_ENREF_17)) and a Lambertian surface reflectance model:

where is the range to the surface and is the area of the LF receiver (0.005625 m^2). During in-flight laser fire testing (see Section 3.2), it was revealed that a constant fraction of each laser’s optical power is internally leaked and measurable by the detector. This leaked power is therefore subtracted from the detected power during this normal albedo calculation.

The received signal is also sensitive the range to the surface. Uncertainty in the range may arise due to uncertainty in spacecraft timing, location, and pointing relative to lunar topography. Lunar Flashlight was not designed to independently measure range (in the way that LIDAR instruments do), but rather depended on navigation to estimate the location and attitude of the spacecraft and models of the lunar surface to estimate the range (Section 4.1). The uncertainty in the range was accounted for into the model but the actual magnitude of the uncertainty would need to have been estimated upon lunar arrival.

## 2.5 Pre-flight testing

Prior to delivery of the LF instrument, a series of end-to-end (ETE) repeatability tests were completed to demonstrate the electronic, thermal, and measurement stability of the science payload as well as reveal any otherwise uncalibrated correlations in the telemetry measurements. For each test, the LF payload was placed in a thermal vacuum chamber and the receiver and detector were cooled to their operational setpoints (248 K and 212 K for the receiver and detector, respectively). The payload was commanded to run in science mode with a repeating laser sequence of Laser 1, Laser 2, Laser 3, Laser 4, Blank (no laser) for ~80 seconds. Within the vacuum chamber the LF lasers were intercepted at 45°incidence by a ground-glass diffuser with a protected gold coating for wavelength uniformity. The diffused beam was directed onto a protected gold mirror which directed a portion of the laser light back towards the LF receiver. To further attenuate the light, a 1-𝜇m pinhole aperture was placed over the LF receiver, centered on the aperture. The light transmitted through the pinhole was reflected onto the LF detector and the flight electronics recorded the detector current as a function of time before “downlink” via the LF Iris transceiver and analysis. Raw data for a single frame of one of the ETE tests (colored by laser firing) is shown in Figure 11. Analysis of these raw data revealed (1) the 40-sample transient period at the start of each laser pulse, (2) numerous single-sample transients for the laser current, detector temperature, and laser temperature, and (3) measurable differences for the detector temperature and laser temperature during the blank pulse. These discoveries influenced the design of the instrument model in Section 2.4.

Chart, line chart

Description automatically generatedFigure 11. Example ETE test raw data for a single 30-ms frame (colors correspond to Figure 10): a) Detector current, b) Laser current, c) Detector temperature, and d) Laser unit temperature.

Appropriate design of the receiver bandwidth involves a balance between sensitivity at the relevant signal frequency (less than the 6 ms laser pulse duration or greater than 166 Hz) and reducing the noise in the amplifier by keeping the bandwidth as low as possible. The LF receiver electronics were designed with a theoretical bandwidth of 714 Hz. The actual bandwidth was estimated from the ETE system testing by measuring the fall time of the detector current when transitioning from laser 4 to laser 0 (Fig. 12). From the LF telemetry, the laser current was observed to fall from 45 A to 0 A in less than 42 μs. The detector current fell from 90% to 10 % in 463 μs. This 90% to 10% fall time can be translated into a bandwidth by using a single-pole lowpass filter model for which the -3 dB bandwidth is equal to 0.35/463 μs, which corresponds to a measured bandwidth of 755 Hz.

Chart, line chart

Description automatically generated

Figure 12. Bandwidth estimation from LF ETE testing. (A) A single measurement frame involving the firing of Lasers 1, 2, 3, 4, and 0 (blank) in sequence, with each pulse being 6 ms in duration. The detector current is shown in blue, while the laser drive current is shown in red. (B) A close-up view of the detector current falling during the transition from Laser 4 to Laser 0 (blank). The black horizontal lines denote the 90% and 10% levels.

The raw data would be further processed with the instrument model described in Section 2.4. The data within the Level 1a LF data product for one of the ETE tests is shown in Fig. 13. Our analysis of the entirety of each ETE test revealed a decreasing trend in the detector current measured when each of the four lasers was firing. This most strongly correlates with the consistently-rising laser temperature, as expected by the laser output power’s inverse dependence on temperature as shown in Section 2.2. Also, the first 10 frames (0.3 s) of each ETE test revealed a steep dropoff in signal, associated with the initial heat up of the lasers, that was ultimately deemed too transient to keep as science data. Finally, we found that the flight electronics occasionally measure unrealistically high variance in the laser current, therefore a local-linear regression filter smooths this data before using it to calibrate the laser wavelength and output power.

Chart, line chart

Description automatically generatedFigure 13. Example Level 1a data over the entire ~80 s collection period for a single ETE test. a) detector current for each laser pulse (colors correspond to Figure 10); b) laser current, where the smoothed laser current data is overplotted in gray; c) detector temperature; and d) laser temperature.

Finally, the ETE Level 1a data would be calibrated to produce a Level 1b data product. The ratio of received laser power to output laser power for a single ETE test is shown in Figure 14. This power ratio is proportional to reflectance and is expected to be constant across all the ETE tests. We note that there appears to be some uncharacterized correlation that consistently appears across all ETE tests for the first 20-30s of data collection.

Chart

Description automatically generatedFigure 14. Example ETE Level 1b data over the entire ~80s collection period, except for the transient 0.3 s at the beginning of the collection.

*2.6 Stray Light Modeling*

Stray light suppression was an important consideration for determining Lunar Flashlight's capability to measure surface reflectance using active laser illumination. We modeled the three-dimensional solar and earthshine illumination of the Moon's poles and the resulting radiation distribution during the primary Lunar Flashlight mission. We then modeled the stray light received at the detector for different optical transmission functions using predicted trajectory data. The results show that suppression of far-field radiation is critical to obtaining usable measurements. The stray light analysis drove design of the detector housing and cover with a turned circular baffle of the correct shape and edge profile to block stray light, described in ([Vinckier et al., 2019](#_ENREF_54)).

Using the solar illumination model described in ([Paige et al., 2010](#_ENREF_37)), we calculated the intensity of reflected solar radiation on each surface facet of the lunar digital elevation model (DEM). We then convolved these solar-band radiances with the spectral response function and optical transmission function of the instrument receiver. This requires knowledge of the spacecraft position above the lunar surface, which was simulated for a nominal set of low-altitude flybys over the south pole.

The illumination model includes direct insolation and earthshine. Multiple reflections among surface elements are included, as is the true lunar topography at a horizontal scale of 475 m/pixel. Surface elements are assumed to reflect radiation uniformly in all directions, i.e., they are Lambertian. Based on this assumption the radiance (W m-2 sr-1) of a surface element with radiosity *F* (W m-2) is . The radiance contribution within a specific spectral band is found by multiplying by the fraction of the integrated solar flux within that band, accounting for the filter transmission :

where is the solar spectral flux (W µm-1) at wavelength , and is the solar radiant flux (W). Typical values of for Lunar Flashlight can be estimated using a boxcar spectral response function:

where is the center wavelength of the band and is its spectral width.

Stray light is modeled as a background contribution to the received signal from the lunar surface. To quantify the background, we calculate the radiation contributions from each surface element as viewed from the spacecraft position. These contributions are weighted by the optical (geometric) transmission function, which typically decreases at larger angles from the center of the field of view (FOV). Figure 15 shows a schematic of the situation.

A picture containing boat, accessory

Description automatically generated

Figure 15. Geometry of the Lunar Flashlight stray light model.

For a distant, small, horizontal surface element in the direction with solar-band radiosity , the power per unit receiver area is:

where is the solid angle of the surface element as viewed from the spacecraft position. Here, the angles and are the polar and azimuth angles measured from the center of the field of view (FOV). For a receiver with a conical FOV with half-angle viewing a uniform horizontal surface extending to the horizon with radiosity , the received flux is:

For a spherical Moon, the horizon angle is , where is the spacecraft altitude. In the case where the receiver is very close to the surface, , we have and for the case of homogeneous isotropic emission. Emission from the lunar surface depends primarily on solar illumination, which also controls surface temperatures. Due to the highly insulating nature of the lunar regolith (e.g., Hayne et al., 2017) surface temperatures are typically close to instantaneous radiative equilibrium, in which case the total reflected solar flux is:

Here, and are the broadband (bolometric) solar albedo and infrared emissivity, respectively, and is the Stefan-Boltzmann constant. Here we assume a square aperture; for a circular aperture with the same diameter the fluxes would be of the reported values. The rate of change of the radiant flux with respect to the angle is useful for calculating the contribution within a small annulus :

Figure 16 shows the radiant flux contributions vs. cone angle for an isotropic surface in radiative equilibrium. More generally, the contribution of radiant flux to each band from a surface element subtending angles and is given by:

and the total power incident on the instrument aperture is:

Chart, line chart

Description automatically generated

Figure 16. a) Incident power and b) Radiant flux contribution vs. cone angle for an isotropic, isothermal surface. The values indicate the equivalent temperature of a surface in radiative equilibrium.

Note that the quantity is the solid angle subtended by the surface element, which for horizontal surfaces is where is the (unprojected) area of the surface element and is the distance from the surface element to the spacecraft. Using the lunar illumination model, we can calculate the received power as a sum of the contributions from the surface elements , to determine the radiant flux incident on the instrument aperture within a spectral band, as viewed from spacecraft position :

where , with being the spacecraft altitude and the distance to the surface element . Given a set of radiosity values and areas of the surface elements from the lunar illumination model, we can then calculate the total received radiant flux for each measurement position .

To model stray light suppression, we define an optical transmission function , which describes the fraction of light from the direction transmitted to the detector. Both geometric blocking of direct radiation (e.g., from a baffle) and suppression of scattered light within the optical system contribute to the transmission function. The form of is discussed below. Accounting for these effects, the measured radiant flux in a given bandpass is then:

Numerically, the integrated contributions of surface elements over the full field of view result in the total measured flux:

where is the optical transmissivity in the direction of element as viewed from position .

Figure 17 shows the geometry of a rectangular baffle. Direct illumination of the mirror is limited to angles and half the mirror surface is shadowed when . The length of the baffle is given by , in units of the primary mirror diameter. Again, the location of a point source at infinity is defined by the angles . Shadowing of the primary mirror by the baffle reduces the source intensity by a factor:

where:

Chart

Description automatically generated

Figure 17. Baffle geometry for stray light modeling from a lunar source (red and blue crescents).

This geometric blocking factor must be applied to all sources at angles along with another factor to account for diffuse scattering by the primary mirror. This second factor is called the *total integrated scatter* (TIS), and is equal to:

for a mirror with 100% reflectivity; we make this approximation here for simplicity, because the errors introduced for an imperfect mirror are small. Only a small fraction of photons incident on the primary mirror from outside the FOV will be scattered onto the detector occupying a small solid angle . In reality, scattering by the primary mirror is described by a bidirectional reflectance distribution function (BRDF), which is a function of both incidence and emission angles; here we only consider isotropic scattering. Finally, at angles a much smaller fraction of photons is scattered from the black baffle walls to the detector. Using these definitions, the optical transmission function has the form:

Examples of transmission functions for a design similar to Lunar Flashlight are shown in Figure 18. In designing the Lunar Flashlight science investigation, we used these approximate transmission functions based on the instrument design, coupled to the lunar surface illumination model, to simulate the background contributions to the received flux as described above.

Chart

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Figure 18. Transmission functions for different baffle lengths, .

# 3. PAYLOAD PERFORMANCE

After development by the Jet Propulsion laboratory, Lunar Flashlight Integration and Test (I&T) activities were performed at the Georgia Institute of Technology (GT) and the Georgia Tech Research Institute ([Cheek et al., 2022](#_ENREF_8)). The GT Space Systems Design Laboratory (SSDL) was contracted to serve as the primary Mission Operations Center (MOC) for the mission, and a team of graduate and undergraduate students supported the mission throughout I&T and operations ([Hauge et al., 2023](#_ENREF_18)).

Lunar Flashlight launched in December 2022 and completed multiple payload activities while in cruise, including basic functionality tests, firing the lasers for increasing lengths of time, slewing the detector across astronomical point sources, and pointing the payload at earth- and space-based assets during Earth perigee to conduct active experiments. These onboard activities validated the in-flight performance of the instrument and exercised the Science Operations pipeline in preparation for science activities. Unfortunately many of these activities did not result in useable data; nevertheless, we describe the activities in detail in the hope that future missions may be able to learn from our planning.

## 3.1 Payload commissioning

Prior to firing the laser, initial payload operations involved human-in-the-loop health tests consisting of heater tests and battery charging. The heater tests were independently performed for the PCM, detector and battery. The PCM and detector heater tests were initiated by setting corresponding duty cycle parameters for each test. After the respective heater temperatures were identified from incoming telemetry, thermal control limits were set with a bandwidth of 2.5 to 3 degrees. Thermal control was successfully enabled until threshold values were reached, after which the system proceeded to cool.

## 3.2 Laser Characterization

During cruise, the team conducted several experiments of increasing duration with no target in view (free space) to characterize the laser unit and detector performance and compare them with ground testing. The first laser firing for checkout activities lasted 3.6 seconds. Subsequent laser firing tests were conducted independently for 10 seconds, 30 seconds, and 90 seconds.

Data from the 90s laser test were processed through the integrated instrument model and compared against the ETE tests (Fig. 19). The current measured during the "blank” (no laser pulse) in each frame is significantly larger during the 90-s laser firing test than as measured on the ground (Fig. 20) due to background starlight. Even so, the single-sample noise properties of the detector for these blank pulses improved over ground testing from 7.6 pA to 6.5 pA. Note that these noise quantities are improved by a factor of 10 within the Level 1a data due to frame-averaging.

Chart, line chart

Description automatically generatedFigure 19. Level 1a data from the 90s laser firing in-flight test. a) Detector current for each laser pulse (colors correspond to Figure 10); b) laser current, where the smoothed laser current data is overplotted in gray; c) detector temperature; and d) laser temperature.

Chart, scatter chart

Description automatically generatedFigure 20. Detector current averaged over each blank pulse as measured a) during ETE testing and b) during the in-flight 90 s laser firing test.

The measured detector current and laser voltage during the laser firing tests revealed an otherwise undiscovered payload configuration change between ground testing and flight: the IDs for the 1064-nm and 1530-nm lasers were flipped, and the IDs for the 1850-nm and 1990-nm lasers were flipped. As shown in Fig. 19, flight data for Laser 1 show that it is the only laser to show minimal dependence on temperature. This contrasts with what was found in the ETE tests, where Laser 2 (1064 nm) would consistently show minimal dependence on temperature. The flight laser voltage data (Fig. 21) similarly reveals that the nominal operating voltages for lasers 1 and 2 are flipped, as well as the operating voltages of lasers 3 and 4. Thus, the in-flight laser order for a nominal 1234012340 firing sequence is 1064 nm, 1530 nm, 1990 nm, 1850 nm.

Chart, box and whisker chart

Description automatically generated

Figure 21. Laser voltage over time during a) ground testing and b) in-flight testing. Laser 1 and Laser 2 appear to have been flipped, while Laser 3 and Laser 4 also appear to have been flipped.

Taking into account the flipped laser IDs and applying the calibrations detailed in the instrument model, we find that there is a measurable internal laser light leakage of approximately 10-11 as a constant fraction of each laser’s output power (Fig. 22). However, this value appears to change slightly between the 10s, 30s, and 90s laser firing tests. The time-weighted average internal light leakage for each wavelength band as a fraction of corresponding laser output power across all three of these laser firing tests is shown in Table 5.

Chart

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Figure 22. Light leakage as a fraction of laser output power for each of the four lasers (1064 nm: blue, 1530 nm: orange, 1850 nm: red, 1990 nm: green) as measured during the a) 10 s, b) 30 s, and c) 90 s in-flight laser fire tests.

Table 5. Average light leakage values during the laser fire tests.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Wavelength Band (nm) | 1064 | 1530 | 1850 | 1990 |
| Light Leakage | 7.1e-12 | 8.2e-12 | 10.1e-12 | 8.8e-12 |

These data were also used to predict the signal-to-noise ratio for a nominal reflectance measurement of the lunar surface. The standard deviation of the light leakage power ratio for the 90s laser fire test was computed for each laser channel and compared against the expected measurement of 0 wt.% water ice on the lunar surface from an altitude of 12.6 km assuming a Lambertian surface model. These associated quantities are all shown in Table 6. Note that the expected return laser power at 12.6 km across all four bands is approximately the same order of magnitude as the measured light leakage power. An SNR of 400 is required to discriminate 0.5 wt.% water ice with 1s significance using a single laser pair ([Vinckier et al., 2019](#_ENREF_54)). To achieve this, around 10 frames, or ~3 seconds worth of measurements, would need to be added together, corresponding to an along-track distance of 5.7 km. In addition, since the light leakage values changed between laser firing tests, the standard deviation of all the tests would need to be considered in the measurement error.

Table 6. Signal-to-noise ratio estimation

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Wavelength Band (nm) | 1064 | 1530 | 1850 | 1990 |
| Reflectance @ 0 wt.% water ice | 0.384 | 0.423\* | 0.438 | 0.445 |
| Power Ratio @ 12.6 km (Lambertian surface model) | 4.33e-12 | 4.77e-12 | 4.94e-12 | 5.02e-12 |
| 90-s Laser Test Power Ratio Standard Deviation | 4.66e-14 | 5.06e-14 | 7.05e-14 | 7.54e-14 |
| Predicted Single-Pulse SNR | 92 | 94 | 70 | 67 |

\*Calculation was for 1495 nm (Vinckier et al., 2019)

## 3.2 Perigee Laser Experiment

The LF team planned to characterize laser power output and stability during cruise by pointing the spacecraft at a telescope on the Earth and observing the laser output. The reason for this observation was to independently characterize the laser output energy, stability, and geometry, so that we could uniquely determine the response from the lunar surface properties.

When it was manifested on the Artemis I mission, the LF trajectory took the spacecraft by a close earth encounter twice before lunar orbit insertion. When LF changed off Artemis to the Hakuto-1 rideshare, the trajectory changed such that LF was on a trajectory to a low-energy capture orbit near a Lagrange point, obviating the Earth flybys. However, after the failure of the propulsion system to put the spacecraft into lunar orbit, Lunar Flashlight made an Earth encounter with a perigee altitude of 64600km. The team quickly planned a set of laser tests to conduct at perigee, which also represented the first opportunity for the spacecraft to actively point at an object other than the sun for the first time.

The perigee track went over Chile and Brazil at closest approach. The Lunar Flashlight team were able to coordinate a short scientific observation of the laser outputs with SOAR in Chile using the Spartan IR Camera ([Loh et al., 2012](#_ENREF_29)). Based on the spacecraft ephemeris, LF would be moving at a few arcsec/s, which is faster than SOAR is able to track, so the observation was planned to track at sidereal rate, with the satellite trailing across the field as the lasers fired in sequence. Three of the four laser passbands could be detectable: 1064, 1535, and 1990 nm (the 1850 nm laser band is in the middle of a strong water absorption and would not reach the Earth’s surface, even in the Atacama). With the 4.1-m primary mirror, the lasers are quite bright (about mag +0.7 in H band), likely to saturate during the minimum 10-second integration time of the IR camera, but the exposure would be long enough to get a few stars in the field at reasonable signal/noise for calibration.

Unfortunately, heavy clouds and rain prevented the SOAR observations from taking place, though several visible-light assets (Cloudstone Brazil, Cloudstone Chile, Pine Park and NOESSAT) observed the sunglint off the passing spacecraft. The Lunar Flashlight spacecraft headed into the sun direction and solar elongation would be small well past the end of the mission, which meant that the laser observation was not able to be replanned.

## 3.4 Detector characterization

After the Earth flyby, the team attempted a detector characterization exercise to collect additional data on the detector response to signals outside of the test conditions, characterize detector stray light response, and understand the detector alignment with respect to spacecraft pointing. Potential sources for an appropriate infrared signal included Mars and Jupiter, which have approximately similar total intensity as our science operations; a full Earth or Moon disk, which would (intentionally) saturate the detector; and Betelgeuse, which would be expected to be below the Lunar Flashlight detection limit (providing a confirmation of the instrument detection limit). During the mission, we only had the opportunity to complete one experiment looking at Mars. The experiment occurred on June 14th, 2023, when the spacecraft was approximately 1.366E6 km from Earth. This activity was implemented by slewing the spacecraft using the AttitudeDither command while the payload was fully on. We used a laser firing sequence of all blanks, meaning that the laser unit and the L-EPS were fully powered but the lasers did not actively fire. The spacecraft slewed along its X-axis across the source so that the source moved in and out of the field of view across the nominal center of the detector. We repeated the experiment across the spacecraft Z axis. The total slew duration was 160s duration while the active data collection occurred over 120 s in the middle of the slew time. Unfortunately, this experiment encountered difficulties in the payload data transfer and the data were unusable for detector characterization.

# 4. SCIENCE OPERATIONS

## 4.1 Planning and Uplink

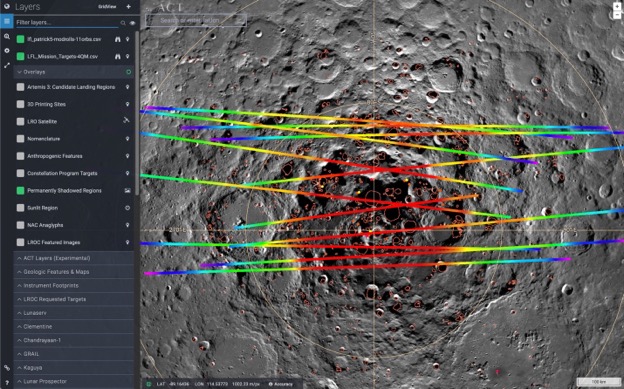
The LF Science Operations Center (SOC), located at UCLA, was responsible for designing and facilitating the science team planning process, processing acquired data for analysis by the science team, and archiving data in the Planetary Data System (PDS) for community and public use. The basis for LF procedures and tools is built on those developed for UCLA’s roles in other previous and current missions, especially LRO Diviner ([Paige et al., 2009](#_ENREF_36)). These were adapted to LF-specific orbit configuration, observation geometry and timing, planning schedule, science measurement goals, and other constraints.

The purpose of uplink planning is to enable the science team to view, consider, and choose the best lunar surface targets to observe during a given lunar perilune orbital pass. The key input is the spacecraft ephemeris, providing location over the orbital pass. Updated ephemerides would be provided by JPL's Mission Design and Navigation (MDNAV) team at prescribed times within an orbit relative to the approaching perilune, and would be downloaded automatically to the SOC. The Diviner-based core of LF targeting tool calculations uses the ephemeris, a lunar surface DEM, and various SPICE kernels describing the instrument, spacecraft orientation, planetary bodies, etc. to calculate a host of observation, spacecraft, configuration, and relationship parameters, including altitude, velocity, observation geometry, lighting, and especially a nadir-pointing ground track (*i.e.,* surface latitude, longitude, and UTC time). This ground track is plotted over imagery and maps of the lunar surface to visualize which regions and features are observable on a given orbital pass.

The output of the LF targeting tool would be visualized in QuickMap, an online lunar GIS developed by Applied Coherent Technology (ACT) Corp and hosted by ASU (https://quickmap.lroc.asu.edu). Leveraging this existing, powerful tool holds several advantages as a mission planning tool. QuickMap is a freely available, web-based tool that is familiar to many users from previous missions or research. It hosts multiple Moon-wide scientific datasets for use as base maps and/or cross-referencing of various surface properties, including derived data such as outlines of permanently shadowed regions (PSRs) that have particularly high importance as LF targets. It also allows the user to query locations and features and retrieve the associated parameters/metadata from multiple datasets. Importantly, QuickMap allows import of custom data in the form of GeoTIFF images of user-created raster data and as text files of coordinate-based points, lines, or polygons and associated user-provided parameter/metadata fields. Based on its incorporation into our end-to-end, tested uplink planning process, we found QuickMap to be an efficient, useful component for lunar instrument observation planning.

The science team planned for active target observation over the Lunar Flashlight science mission phase, considering multiple mission constraints. Sufficient signal-to-noise in measurements were expected at a spacecraft-to-surface range of ~20 km and lower, based on forward modeling estimates. The mission design generally brought the spacecraft closest to lunar surface (perilune) along the ground track’s southernmost extent, but this track didn't always cross the geographic south pole. Pre-launch thermal constraints limited instrument operation to ~90 seconds total per perilune pass, within 20 km altitude of the lunar ellipsoid and ~5 degrees latitude of the south pole. The spacecraft was expected to hold a nadir or near-nadir (within a few degrees) pointing over the perilune pass, which would largely dictate which parts of the surface would be observable, given LF’s narrow ~100 m-wide field of view. A total of 10-13 science passes were planned during the primary mission lifetime, so covering the multitude of environments and parameters necessitated the science team to create a tradespace of planned targets over the whole mission lifetime, and for the SOC to enable the team to rapidly replan upcoming perilune passes as real-time data were generated.

The LF targeting tool calculations and outputs to QuickMap-compatible format were tailored to incorporate the above constraints and flexibilities in a way to maximize efficient surface-target visualization, discussion, selection, and conveyance to the GT ops team. Ground tracks are displayed (Fig. 23) as points at 1-second intervals, allowing quick visual inspection of durations and offsets by users. Points are colored by range from spacecraft to surface, considering spacecraft altitude, view angle, and actual surface elevation, allowing quick assessment of relative data signal quality. By clicking on any point on the ground track (Fig. 24a), users can query for included parameters from the targeting tool metadata, including exact locations, time, and altitude. The team produced high-resolution, photometrically modeled maps of the south polar region for each planned perilune passes to use as custom basemaps showing illumination conditions as they would be during observations. Users could choose to use these base maps and color the ground track points by lighting state to determine if they would be sunlit or shadowed at time of observation.

Figure 23. Lunar Flashlight targeting tool output for a set of example perilune passes, displayed using QuickMap on a basemap of LROC WAC imagery and with the PSR shapefile displayed (orange lines). The data are displayed as dots at 1 s intervals and color coded for spacecraft altitude relative to the actual surface topography (red = closest to the surface; blue = furthest from the surface).

Map

Description automatically generatedFigure 24. Lunar Flashlight targeting tool output for a set of example perilune passes, displayed using QuickMap on a basemap of LROC WAC imagery and with the PSR shapefile displayed (orange lines). a) users can query any point along the ground track for data parameters. b) The instrument planned ON times (in green) could be retrieved for inclusion in the IOP.

Using the targeting tool output and QuickMap display, science team members would create an Instrument Operation Plan (IOP) for each perilune pass. For each predicted pass geometry, the science team would choose the experimental parameters that would best serve investigation science goals, including instrument on and off times (Fig. 24b), pointing (on- or off-nadir), and laser firing sequence. The experiment parameters would be encoded into the IOP for GT to implement. GT would provide a file back to the science team confirming the ground tracks after SC encoding.

The science team uplink activities would largely be driven by the delivery schedule of updated ephemerides. After lunar orbit insertion, the mission planned to make a nominal ephemeris available that covered every orbit of the nominal mission. The science team would use this to deliver a set of nominal IOPs providing a comprehensive view of the observations possible over the entire mission measurement period. This would be useful to understand and optimize the distribution of environments, conditions, and scientifically informative targets over the entire mission. Of particular interest were perilune pass crossing points of different orbits, which would allow repeat measurements under different conditions.

During mission operations, the planned and actual spacecraft orbital maneuvers would be used to refine the science IOP requests for each orbit. During each orbit, implementing the IOP would be the primary responsibility of one science team member (the Science Uplink Lead, or SUL). They would keep track of ephemeris updates, create a notional observation plan, present the notional plan and options in a discussion with the whole science team, create the IOP file based on resulting consensus decisions, be the point of contact with other LF teams, and attend to highly time-constrained turnarounds or adjustments. The whole science team would participate in the primary IOP creation meeting, which could be held during working hours. Notably, the LF targeting tool would be accessible to team members to run online and download outputs, which they could then upload to the openly available QuickMap. This would facilitate participation not only by the SUL, but also in the team-wide discussion, independent exploration of targets and strategies, and “following along” with plan evolution over the orbit.

## 4.2 Downlink, Analysis, and Archiving

For data generation and downlink, JPL provided baseline tools to Georgia Tech, and additional tools and software were developed by GT operators ([Starr, 2023](#_ENREF_49)). Experimental data was generated by the science instrument at a rate of approximately 1 MB per experiment second. Raw data was copied from the payload electronics to the spacecraft C&DH filesystem. Science experiment files were downlinked in segments to the Mission Operations Center at Georgia Tech, where GT concatenated the files and converted them to human-readable .csv format. The data conversion tool provided raw data number (DN) and engineering unit (EU) outputs, as well as PNG and interactive HTML plots of the data for quick review. The GT process also converted the experiment timestamps (which begin at zero for each experiment) to the spacecraft clock times, with approximately 1 ms-level accuracy. The MOC would also provide an attitude pointing file (.ck) derived from spacecraft telemetry and the JPL Navigation team would provide a reconstructed trajectory file.

During the mission, the UCLA SOC would facilitate processing the experimental data through the instrument model (Section 2.4) to derive calibrated data products and using the attitude pointing and trajectory information to determine actual instrument pointing and altitude. For each orbit, one science team member (the Science Downlink Lead, or SDL) would be responsible for ensuring the data were fully downlinked and processed, that the data were complete and scientifically useful, for reporting any anomalies to the spacecraft operations team, and for briefing the science team on preliminary results during team meetings, including visualizing the actual instrument pointing tracks in QuickMap.

The LF data were slated for archival in the PDS Geosciences node following planetary science mission protocols. Three levels of data would be archived along with the appropriate PDS4 XML labels and an LF Data User Guide (Table 7). Unfortunately, no suitable data were collected to be archived.

Table 7. Planned Lunar Flashlight PDS data products.

|  |  |
| --- | --- |
| **Level** | **Description** |
| **L0 (Archived)** | * Raw data from the LF instrument converted from binary into engineering units |
| **L1a** | * Raw data averaged over each pulse within every frame of laser pulses |
| **L1b (Archived)** | * Received power for each wavelength channel based on receiver responsivity * Laser power emitted within the receiver field-of-view for each channel * Centroid wavelength for each channel |
| **L2 (Archived)** | * Normal albedo for each wavelength channel, generated using spacecraft telemetry to determine the range, latitude, longitude, and a Lambertian surface model |

# 5. LUNAR FLASHLIGHT MISSION SUMMARY AND STATUS

Though originally selected as a secondary payload on the Artemis I mission, Lunar Flashlight experienced setbacks in schedule related to parts development, principally the propulsion system, and was not ready in time for Artemis I integration. NASA worked to find a rideshare and Lunar Flashlight launched on December 11th, 2022, as a secondary payload to HAKUTO-R on a SpaceX Falcon 9 vehicle. The Lunar Flashlight spacecraft successfully deployed on a translunar trajectory and the onboard autonomous subsystems activated nominally. Contact with the Deep Space Network occurred soon after the spacecraft achieved stable sun-pointed control. The team activated the propulsion system in the first few contacts with fuel priming and commissioning but discovered anomalous thrust levels during the first programmed momentum desaturation. During the next five months, troubleshooting, testing, and recovery activities were performed with the goal of completing the trajectory maneuvers and the lunar orbit insertion burn. However, the spacecraft failed to achieve sufficient propulsive control to execute a lunar capture maneuver and Lunar Flashlight passed by the Earth and Moon on May 16, 2023, in a permanent, heliocentric orbit. The most likely cause of LF propulsion system failure is foreign object debris from the 3D printed titanium tank/manifold lodging in the fuel lines to the thrusters, obstructing fuel delivery ([Smith et al., 2023](#_ENREF_45)). This failure did not permit LF to achieve its science goals before the mission came to an end in June 2023.

Despite not achieving lunar orbit, Lunar Flashlight proved to be an extremely successful technology demonstration mission, meeting or exceeding all its technology-focused mission goals. The newly-developed propulsion system components were extensively tested under unusual and extenuating circumstances, generating a rich dataset for future design and testing. The propulsion system accumulated >90 minutes of nominal thrust data and preliminary ISP calculations show that the ASCENT fuel itself performed as expected. The Sphinx flight computer successfully performed in a deep space radiation environment. The Iris radio successfully demonstrated a new precision navigation capability that can be used by future small spacecraft to rendezvous and land on solar system bodies. The partnership between the managing institutions and the performance of the student-led GT operations team demonstrated the ability for small satellites to be successfully operated in this mode ([Hauge et al., 2023](#_ENREF_18)). The mission also captured several portraits of the Earth and Moon using its star trackers (Fig. 25).

A picture containing blur, light, night sky

Description automatically generatedFigure 25. Portrait of the Earth and Moon taken by Lunar Flashlight's star tracker on UTC 2023-03-23T05:11:55 (May 22, 2023), when the spacecraft was approximately 750,000 km from the Earth.

Finally, as described in this paper, the Lunar Flashlight laser reflectometer was also exercised in flight, showing that its laser unit and detector functioned as expected and matched the ground test data. Because of the budget and risk profile associated with Cubesat missions, the instrument ground test campaign was extremely compressed and pushed many of the characterization activities to flight. We recommend that future versions of instruments similar to Lunar Flashlight include the following in ground testing: measure the laser output power and variability using a reference pick-off; characterize the detector response function at different temperatures, including the expected flight temperature; calibrate the absolute responsivity of the receiver for each laser wavelength after the integration, including the throughput of the optics; and measure the reflected light from a known surface.

Key advantages of the active spectroscopy technique for lunar volatile scouting are that it enables measurement of surface reflectance in locations and conditions where passive spectroscopy cannot operate, specifically nightside locations where no indirect lighting is available, and in the deepest parts of PSRs where indirect lighting may be too faint for passive spectroscopy. From the ground and flight data, the anticipated performance of the LF instrument would likely have been able to use active illumination spectroscopy to meet the measurement success criteria for the Lunar Flashlight mission. Unfortunately, the active laser spectroscopy technique could not be verified as the mission did not encounter a solid surface. However, future missions using this technique have a sound basis for instrument design, verification, and use.

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