NASA's Lunar Trailblazer Mission: A Pioneering Small Satellite for Lunar Water and Lunar Geology

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***Abstract*— Selected in 2019 as a NASA SIMPLEx mission, Lunar Trailblazer is in implementation for flight system delivery at the end of 2022. The mission's goal is to understand the form, abundance, and distribution of water on the Moon and the lunar water cycle. Lunar Trailblazer also collects data of candidate landing sites to inform planning for future human and robotic exploration of the Moon and evaluate the potential for in situ resource utilization. Lunar Trailblazer's two science instruments, the High-resolution Volatiles and Minerals Moon Mapper (HVM³) and the Lunar Thermal Mapper (LTM) provide simultaneous high-resolution spectral imaging data to map OH/water, crustal composition, and thermophysical properties from a 100±30 km lunar polar orbit. The ~210-kg flight system deploys from an ESPA Grande and utilizes a ~1000 m/s ΔV hydrazine chemical propulsion system, similar to that employed by GRAIL. Trailblazing elements include the novel state-of-the-art dataset collected at substantially reduced price point, fully geographically co-registered data products delivered to the Planetary Data System, planetary mission team demographics, Caltech campus mission operations, and student staffing of select mission ops roles. Lunar Trailblazer's pioneering development is providing key lessons learned for future planetary small spacecraft.**

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1. INTRODUCTION

Lunar Trailblazer is among the first generation of planetary science smallsats, which were initially conceived to fly as rideshares, utilizing CubeSat and ESPA-family deployers for release of spacecraft, which then travel independently to their destinations. In June 2019, NASA selected Lunar Trailblazer as one of three missions to be flown as part of the second Small Innovative Missions for Planetary Exploration (SIMPLEx) call. A 12-month Phase A/B development culminated in a Preliminary Design Review in October 2020 and mission confirmation in November 2020. Lunar Trailblazer has since passed its Critical Design Review in July 2021 and is in the implementation phase. Lunar Trailblazer will deliver its flight system in October 2022. NASA has currently manifested Lunar Trailblazer on the Interstellar Mapping and Acceleration Probe (IMAP) in 2025; NASA is examining possibilities for an earlier launch.

Implemented as a Class-D 7120.5e mission, Lunar Trailblazer is a PI-led mission at Caltech, managed by JPL. Lockheed Martin Space provides the spacecraft and

Figure 1. Digital rendering of Lunar Trailblazer at the Moon (graphic by Lockheed Martin Space)

integrated flight system (Figure 1). Science and mission operations will be led from Caltech with mission design and navigation at JPL. The spacecraft carries two science instruments that image simultaneously: a visible/shortwave infrared imaging spectrometer, the High-resolution Volatiles and Minerals Moon Mapper (HVM^3), similar to the Moon Mineralogy Mapper (M^3) but explicitly designed to measure hydrated materials, and the Lunar Thermal Mapper (LTM), a multispectral thermal infrared imager to measure temperature, composition, and thermophysical properties. A student collaboration option funded by NASA involves undergraduate students at Caltech and Pasadena City College in science mission planning and mission operations.

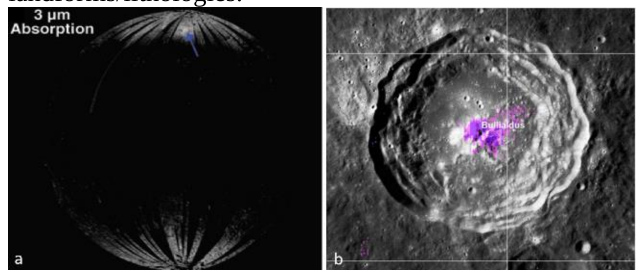
Here we describe Lunar Trailblazer's science, instruments, mission design, and flight system. We also describe the rationale, challenges, and changes made along the way as Lunar Trailblazer pioneers a small spacecraft approach, offering some suggestions on lessons learned.

2. WATER ON THE MOON: BIG SCIENCE AMENABLE TO SMALLSAT INVESTIGATION

Lunar Water: Key Questions

Water on the Moon was one of the most exciting, mostly unexpected discoveries of the late 2000's. The canonical view of lunar formation at the time was accretion from giant impact materials that were volatile-poor due to losses to space, leading to a dry mantle and water-poor magmas. Meanwhile water ice and other volatiles had long been hypothesized at the poles [Watson et al., 1961] and were suggested by Lunar Prospector neutron spectrometer data showing hydrogen enrichment at the poles [Feldman et al, 1998]. In 2008, Saal et al. [2008] measured volatiles in Apollo lunar glasses in laboratory, finding mantle-derived magmas were enriched in water to levels comparable to Earth's mantle. In 2009, the LCROSS mission that impacted into a permanently shadowed region (PSR) in Cabeus crater detected H_2O ice [Colaprete et al., 2010], confirming

Figure 3. On the sunlit Moon Lunar Trailblazer examines OH/H_2O discovered by M^3 in (a) latitudinal gradients and (b) elevated concentrations associated with landforms/lithologies.



inferences from a variety of remote sensing measurements and modeling (summarized in Hayne et al. [2014]) (Figure 2). In 2009, OH and/or H_2O were detected on the sunlit surface of the Moon by the shortwave-infrared (SWIR) spectrometer, Chandrayaan-1/M^3, and confirmed by reanalysis of data in the EPOXI/HRI-IR and Cassini/VIMS flyby datasets [Pieters et al, 2009; Sunshine et al., 2009; Clark et al., 2009] (Figure 3). Broadly distributed, potentially time-variable OH/H_2O was found at high latitudes [Sunshine et al., 2009; Li & Milliken et al., 2016; Wöhler et al., 2017; Bandfield et al., 2018], and certain regional landforms, e.g. select domes and impact crater central peaks, were found to be locally enriched in OH, H2O [Klima and Petro, 2017; Li and Milliken, 2017].

Nonetheless, key questions remain about lunar water, as well as the water cycle on airless bodies more generally, highlighted in the Decadal Survey [*Visions & Voyages*, 2011]. M^3 provided the best spatially-resolved (70-280 m/pixel) coverage for OH/water detection; however, because the discovery of water on the sunlit Moon was not expected, M^3 was not optimized to rigorously quantify its abundance. M^3's 3-μm cutoff wavelength results in ambiguities in the strength, shape, and exact position of the absorption band, which are critical for quantifying the abundance and form of hydrated species. Thermal emission further complicates the data, as thermal radiance needs to be removed from reflectance to accurately quantify the water band depth. Discrepancies exist between different investigators' thermal correction techniques, leading to conflicting results about whether the species is more likely water or hydroxyl, where it is concentrated, its abundance and whether it migrates over the course of

Figure 2. Lunar Trailblazer examines permanently shadowed regions at the lunar poles. (a) neutron spectrometer maps that show elevated hydrogen at up to 0.5 wt% H_2O equivalent at coarse scale (few km; NASA/GSFC/SVS/Roscosmos) (b) Lunar Trailblazer would detect and localize water at 100s m/pixel within specific permanently shadowed regions (artist's conception Caltech/PCC/Hongyu Cui).

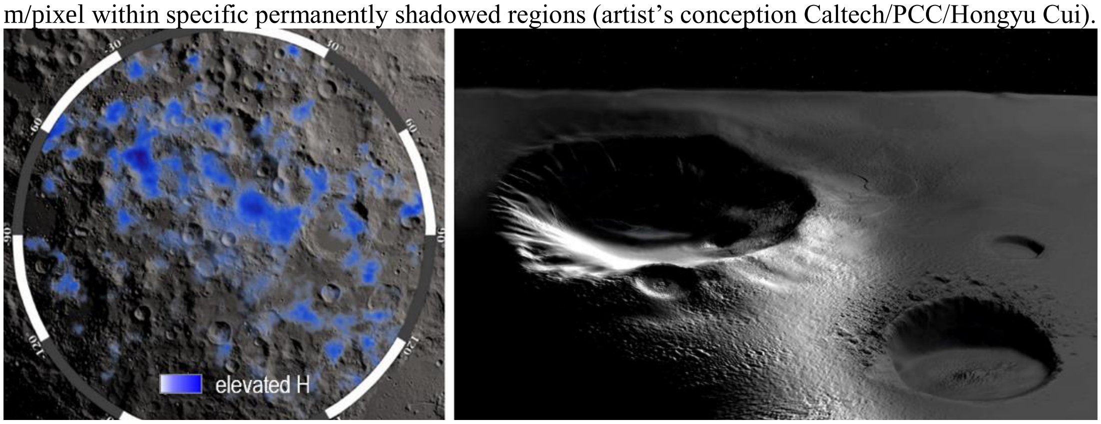
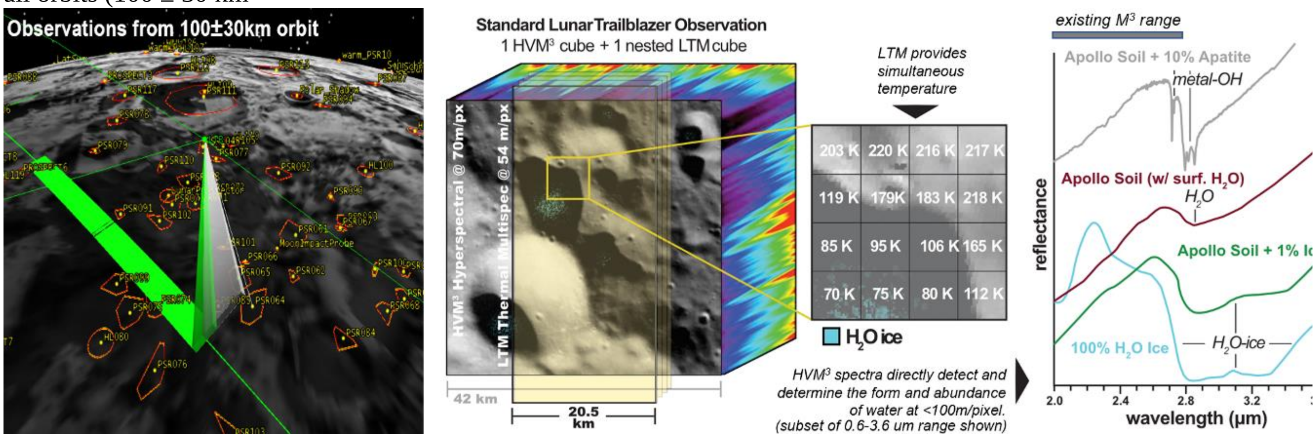


Figure 4. The Lunar Trailblazer spacecraft acquires simultaneous images from its two instruments for mapping the form, distribution, and abundance of water as well as mineral composition, and thermophysical properties at <100 m/pixel from all orbits (100 ± 30 km



the lunar day [e.g., Li & Milliken et al., 2016; Wöhler et al., 2017; Bandfield et al., 2018]. Coarse resolution hydrogen enrichments in gamma ray and neutron spectrometer data only partially follow locations of M^3 detections of OH/H_2O. Some PSRs have water ice, including those directly detected with M^3 using terrain-scattered light [Li et al., 2018]. Many others have temperature data implying water could be stable or albedo properties suggesting water might be present but have no water ice detections [Hayne et al., 2014].

Mission Science Goals and Objectives

Lunar Trailblazer's coordinated datasets improve upon the state of the art to achieve the science goal and objectives (Figure 4; Table 1). Lunar Trailblazer's goal is to understand the form, abundance, and distribution of water on the Moon and the lunar water cycle, resolving outstanding questions. The mission is optimized to make targeted measurements of the infrared properties of the lunar surface. Mission objectives are to (1) detect and map water on the lunar surface at key targets to determine its form (OH, H_2O, or ice), abundance, and distribution as a function of latitude, soil maturity, and lithology; (2) assess possible time-variation in

Table 1. Current best estimate Lunar Trailblazer science observing parameters from 100±30 km orbit compared to M^3 and Diviner

	HVM^3 CBE	M^3 as flown
Spatial Sampling	50-90 m/pixel	70-300 m/pixel
Spectral Range	0.6 – 3.6 µm	0.4-3.0 µm
Spectral Sampling	10 nm	12.5 nm
# Data Cubes*	≥1000	80% global
Temporal	>3x/day	Multiple times of day
	LTM CBE	Diviner as flown
Spatial Resolution	40-70 m/pixel	~200 m/pixel
Thermal	110-400K (±<2 K) 4 broad bands, 6-100 µm	30 – 400K 2 solar and 4 broad bands, 0.3 – 400 µm
Composition	7-10 µm, 11 channels; < 0.5 µm width	7.5 -9 µm, 3 channels; < 0.5 µm width
Temporal	>3x/day	Full daytime
# Data Cubes*	≥1000	global

lunar water on sunlit surfaces; and (3) map the form, abundance, and distribution of water ice in the PSRs, finding any operationally useful deposits of lunar water and locations where it is exposed at the surface for sampling. In all cases, Lunar Trailblazer simultaneously (4) measures surface temperature to quantify the local gradients and search for small cold traps. The Level-1 requirements of the mission flow from these objectives.

Bonus Science: Other Volatiles, Crustal Composition, Landing Site Reconnaissance, and ISRU

Lunar Trailblazer collects data that also address other key lunar science and exploration priorities. These include

(1) fundamental lunar science by mapping soil and rock composition (mineralogy, space weathering). HVM^3 provides data for assessing mineralogy and space weathering at higher spatial resolution than M^3 while LTM improves the fidelity of characterization of silicate mineralogy via additional compositional channels around the Christiansen feature (Si-O stretch) with higher spatial resolution than the Diviner Lunar Radiometer (Diviner) on board the Lunar Reconnaissance Orbiter (Table 1).
(2) landing site reconnaissance for maps of water, composition, and thermophysical properties for traverse planning for both robotic and human missions. Lunar Trailblazer's data provide the first maps of water ice and rock composition at actionable scales to drive decision-making for efficient navigation to targets for in situ investigation (<100 m/pixel) (Figure 5);
(3) zonal targets for comprehensive, high-resolution surface and thermophysical properties mapping for ISRU reserve assessment. Lunar Trailblazer will determine surface exposure for sampling, extractability (slab ice vs. ice frosts vs. ice in pores), and high-resolution spatial distribution to inform operational scenarios.

Lunar Trailblazer is also expected to have margin against its originally planned data volume budget, particularly following the project's summer 2021 decision to add a

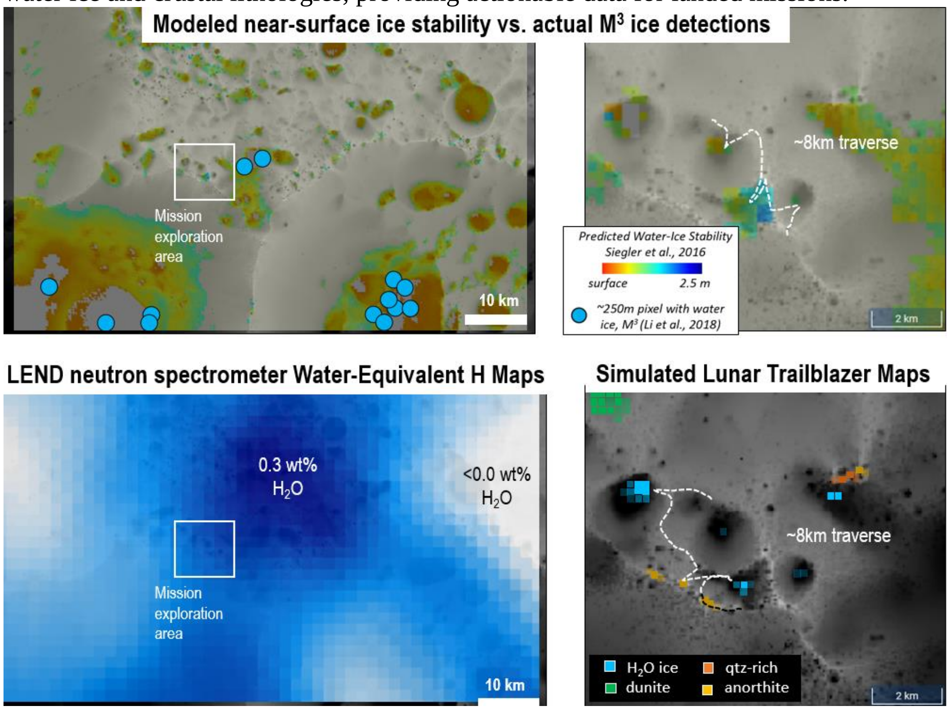


Figure 5. Existing lunar neutron spectrometer data do not provide data of water ice distribution at scales actionable for landed mission planning. Some discrepancies exist between predicted models of water ice occurrence and actual detection of water ice in other datasets. Lunar Trailblazer enables maps at <100m/pixel scale of the distribution of water ice and crustal lithologies, providing actionable data for landed missions.

medium-gain antenna (MGA). As such, Lunar Trailblazer has reached out the community for additional targets via workshops in October 2021 and a target input website, similar to the "HiWish" process of the Mars Reconnaissance Orbiter/HiRISE instrument (see section 6).

3. Mission Design, Science Instruments, and Dataset

Mission Design

Following separation from the launch vehicle, Trailblazer uses its chemical propulsion system to enter into a ~100-km polar orbit around the Moon. For a trajectory with IMAP, cruise, lunar orbit insertion, and period reduction to the science orbit take 4-7 months, depending on the lunar phase at launch. The Moon has a heterogeneous gravity field and so Lunar Trailblazer maintains its 100±30 km science orbit via orbital maintenance maneuvers, approximately every 3 months.

HVM^3 and LTM acquire data simultaneously along-track in pushbroom mode for targets selected by the science team for a particular planning cycle, rolling up to 8 degrees across track. Over Trailblazer's ≥1-year primary science mission, each instrument will acquire ≥1000 targeted images of the Moon and additional data for calibration. Targets include ≥800 sites to determine the lithology and water content of the surface, and ≥50 of these locations at ≥3 times of the lunar day to determine whether volatile composition changes with temperature. In PSRs, ≥150 targets will be acquired to search for ice and determine the volatile content and composition of all PSRs, using terrain-scattered light and coverage of multiple latitudes. HVM^3 can be run in 4.4 Hz mode (~5x longer integration time) to yield coarser spatial resolution but higher SNR in these shadowed regions.

HVM^3: High-resolution Volatiles & Minerals Moon Mapper

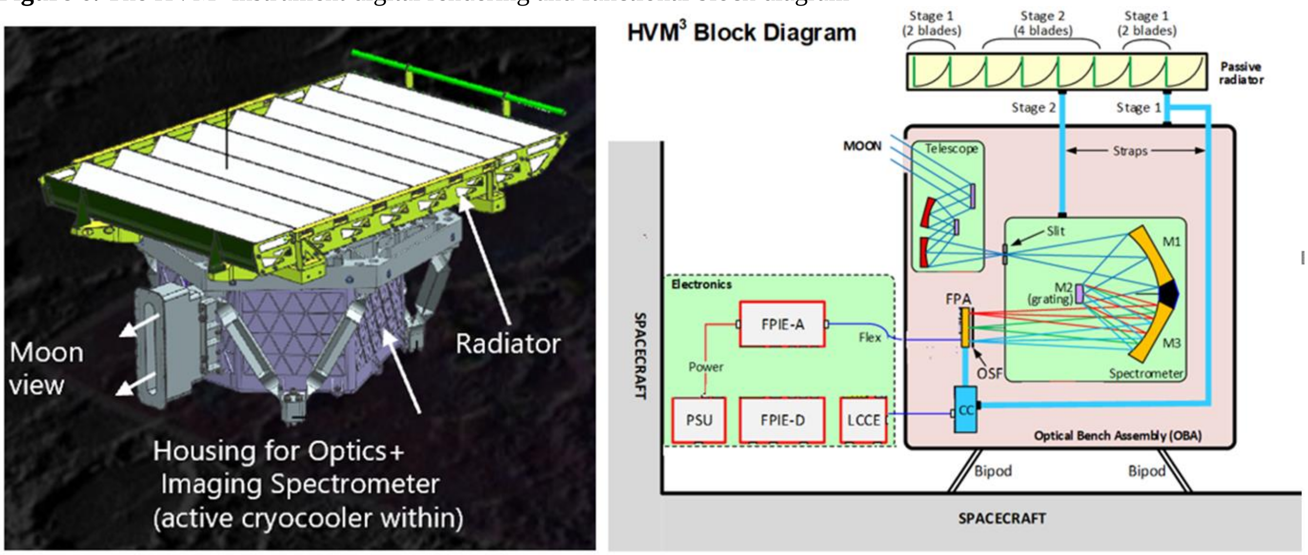
HVM^3 instrument—HVM^3 is a JPL-built, modernized version of the successful M^3 imaging spectrometer and has been optimized to identify and quantify water. A spectral range of 0.6 to 3.6 µm with spectral sampling of 10 nm enables sensitive discrimination of the form and abundance of even small amounts of water by discrimination of the absorption band centers of bound OH/H_2O versus H_2O ice. The wavelength range is also sensitive to other volatiles, including CO_2, CH_x, NH_x, and sulfur species. Longer integration times (5x) enable this capability within PSRs.

HVM^3 is an Offner imaging spectrometer based on the UCIS design, which was matured to TRL-6 under MaTISSE funding [Van Gorp et al., 2014]. The HVM^3 telescope and spectrometer optics are made entirely of reflective surfaces. It uses a dispersive grating with efficiency tuned to improve signal in the low-illumination longer wavelength regions of the spectrum. Figure 6 shows the optical layout, and Table 2 below shows the nominal performance. The thermal control architecture of HVM^3 consists of active and passive elements. It leverages the passive cryogenic cooler design developed for M^3 [Rodriguez et al., 2009] that had a similar orbit. The first stage of the HVM^3 passive cooler is used to reject the heat of a Lockheed Martin Micro1-2 cryocooler that is used to cool the FPA. The second stage of the passive

Table 2: Current best estimate HVM^3 performance

Parameter	Estimated Capability
Spectral Range	600 to 3600 nm
Spectral Sampling	10 nm
Spectral Response	15 nm
Spectral Calibration	Knowledge within 5%
Radiometric Calibration	Knowledge within 10%
Signal to Noise Ratio	Example in Figure 7
Cross-Track Uniformity	Spectral calibration 10%
Spectral Uniformity	IFOV 10%

Figure 6. The HVM^3 instrument digital rendering and functional block diagram

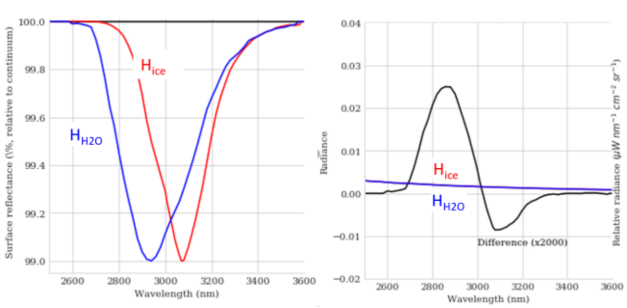


cooler is used to passively cool the spectrometer and telescope.

HVM^3 Performance Model— HVM^3's performance-driving observation is the discrimination of ice and molecular H_2O in PSRs via scattered light, the most challenging and "performance-driving" case, requiring a ~1 part per 100,000 sensitivity. Our typical PSR illumination estimate assumes a 1W/m^2 irradiance. The band depth criterion of all features and differential changes is 1% relative to the continuum; i.e., we aim to discriminate ice and molecular H_2O in PSRs for a 1% absorption depth. This captures the most useful minimum level of ice abundance (100-1000 ppm) that would be useful for resource extraction and provides a comfortable floor for detecting trace water elsewhere. The 3-µm region is the lowest illumination, and 1.5 and 2.0 µm absorptions due to crystalline ice will have greater signal for discrimination.

We evaluate the associated SNR needs by simulating absorptions (Figure 7) for the PSR case as continuum-relative ratios. We translate these into radiance observed at the sensor.

Figure 7. (a) The most challenging HVM^3 performance reference case tests two hypotheses of the surface, portrayed by continuum-removed features of ice and molecular H_2O at 1% band depth at the lowest light 3.0 µm feature. (b) The two hypotheses expressed in radiance units require part per hundred thousand separability



We then calculate the SNR using standard instrument modeling and component performance assumptions. The PSR reference case provides SNR that achieves discriminability to within $p<0.03$, with for ~0.25 km^2 areas. More typically, with multiple spectra over an area, the true p-value is orders of magnitude better. In the most challenging of the HVM^3 observations, estimated instrument performance provides margin against the Trailblazer science objectives.

LTM: Lunar Thermal Mapper

LTM Instrument— LTM is a UK-contributed, University of Oxford-built miniaturized thermal infrared multispectral imager, optimized to simultaneously measure temperature, composition, and thermophysical properties. LTM has substantial heritage from miniaturization efforts carried out for the Compact Modular Sounder instrument for TechDemoSat-1. LTM uses a five-mirror optical system and uncooled microbolometer detector array to map the lunar surface (Figure 8). The infrared filters for compositional and temperature mapping are mounted at an intermediate focus. Radiometric accuracy of the instrument is maintained by viewing an onboard blackbody calibration target and space with a motorized pointing mirror.

LTM Surface Temperature Investigation—LTM's main function is to provide an independent estimate of surface temperature to augment the thermal correction procedure for the HVM^3 instrument in the ~3 µm region and understand co-variance of water content with temperature. LTM is co-aligned with HVM^3 to capture the temperature of the surface contemporaneous with HVM^3 field of view observation.

LTM carries four temperature channels for identification of cold traps and the required ±5 K discrimination of temperature on the lunar surface. This is achieved using a combination of four relatively broadband infrared channels that span 6.25 to 100 µm (Table 3) with roughly equal

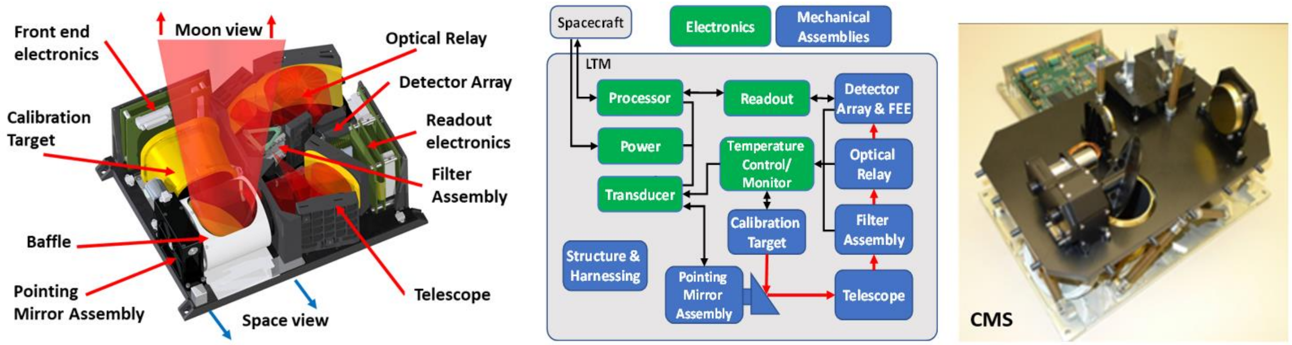


Figure 8. The Lunar Thermal Mapper instrument (left, center) is based on the Compact Modular Sounder (right), flown on TechDemoSat-1

logarithmic wavelength spacings.

LTM Composition Investigation—LTM expands on the highly successful Diviner compositional investigation [Paige et al., 2010] by including eleven narrow (~40 cm^{-1}) compositional channels from 7 – 10 µm (Table 3) to measure the Christiansen feature (CF), extending prior 3-channel maps at the Moon by the Diviner instrument to better discriminate silicate lithologies, particularly the most silicic and mafic endmembers. LTM's baseline set of infrared channels (Table 3) includes the three compositional channels that are currently in orbit around the Moon as part of the Diviner experiment. This will allow cross-calibration and improved spatial resolution from Trailblazer's nominal 70 - 130 km operational orbit (~40 -70 m/pixel for LTM and ~200 m for Diviner). These eleven channels interrogate the position and shape of the Christiansen feature (CF). Science targets for LTM's compositional investigation include: (a) the highly silicic constructs that were identified by their short (<7.8 µm) CF positions; (b) Mg-spinel lithologies that occur in small (~ <5 km) exposures in multiple geological settings; (c) Possible mantle exposures near impact basins by examining the ratio of olivine to plagioclase (dunite vs. troctolite); (d) Irregular Mare Patches with scales of 100-5000 m where Trailblazer's higher spatial resolution will provide fully spatially resolved multi-spectral maps for the first time.

Table 3. Baseline filter set for the Lunar Trailblazer Lunar Thermal Mapper. The current design includes eleven channels for compositional mapping and four channels for surface temperature mapping.

Filter (µm)	Measurement Type	Filter Type
7	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
7.25	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
7.5	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
7.8	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
8	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
8.28	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
8.55	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
8.75	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
9	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
9.5	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
10	Composition	Interference $\Delta\nu \approx 40 cm^{-1}$
6.25 -12.5	Thermal	Interference
12.5 - 25	Thermal	Interference
25 -50	Thermal	Mesh
50-100	Thermal	Mesh

Coordinated Science Data Products

Trailblazer's dataset will comprise the highest spatial and spectral resolution shortwave infrared and mid-infrared maps to determine lunar volatile distribution and abundance, surface composition for geology, and surface thermophysical properties. If mission data return and mission duration permit, as it satisfies its science objectives, Lunar Trailblazer will acquire additional data of high priority to the lunar science and exploration community, including geologic investigations of lunar lithologies (e.g., irregular mare patches, silicic domes, Mg-spinel-rich locations, dunite/troctolite regions, pyroclastic deposits) and reconnaissance for candidate landing sites.

Lunar Trailblazer's data products will be delivered to the Planetary Data System (PDS) at 3-month intervals. Additionally, autoprocessed quick-looks will be available

Table 4. Current best estimate Lunar Trailblazer science observing parameters from 100±30 km orbit

HVM^3	
Spatial Sampling	50-90 m/pixel
Swath Width	30-55 km
Spectral Range	0.6 – 3.6 µm
Spectral Sampling	10 nm
SNR	>100 at reference
Uniformity	>90% cross track
# Data Cubes*	≥1000
LTM	
Spatial Resolution	40-70 m/pixel
Swath Width	14-27 km
Thermal	Temp. retrieval 110-400K (± <2 K) 4 broad bands, 6-100 µm
Composition	7-10 mm 11 channels; < 0.5 µm
# Data Cubes*	≥1000

within 24 hours of downlink on the lunar Trailblazer website. A key feature of Lunar Trailblazer's data products is that they will be delivered to the PDS quantitatively co-registered. This is unusual for planetary satellite remote sensing data, where typically navigation data is obtained from SPICE kernels (the information system of the NASA Navigation and Ancillary Information Facility; NAIF), and co-registration is performed by end-users on an as-needed basis depending on the science or engineering question being addressed. The science goals of the Lunar Trailblazer mission described above require precise registration of HVM^3 and LTM at a level of fidelity beyond what is expected from SPICE alone. Further, HVM^3 must be photometrically corrected using lunar topography, which will serve as a basemap for registration of all Lunar Trailblazer data to the surface. Thus, we will be performing both image-to-ground registration (HVM^3 to LOLA or LOLA & Kaguya) and image-to-image registration (LTM to HVM^3). These higher level data products, control networks, and residuals will be delivered to the PDS with the imaging data so that users understand the quality of the registrations that have been performed.

Automated feature matching will be used to perform both image-to-ground and image-to-image registrations. An array of feature matching algorithms are available and will be iterated over to find the best registration based upon the number of tie-points, the distribution of those points and the residuals returned after matching. From previous efforts using similar data [Boardman et al., 2011], manual tie-pointing will be utilized for the small subset of data for which algorithms do not converge so as to deliver a fully co-registered set to the PDS.

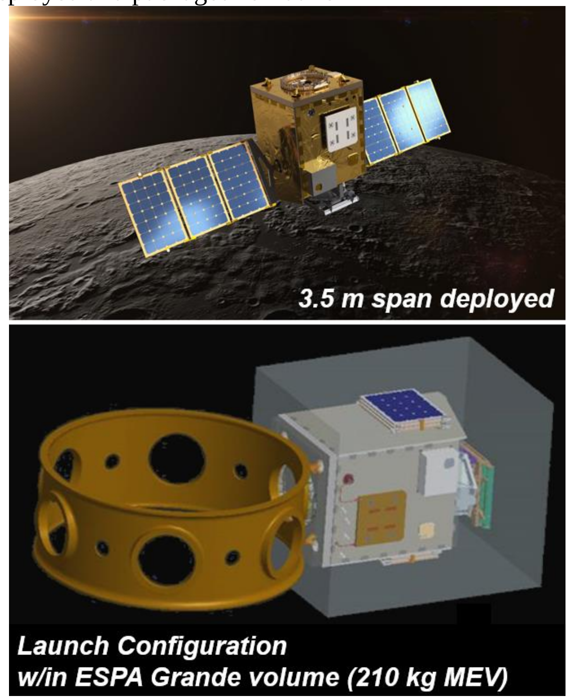
4. FLIGHT SYSTEM

The Lunar Trailblazer spacecraft is built and the flight system integrated by Lockheed Martin Space in Littleton, Colorado. Lunar Trailblazer is designed to deliver the ~20-kg science payload to polar lunar orbit, has an MEV mass of 210-kg, and fits comfortably within an ESPA Grande volume. When deployed, the solar panels have a span of 3.5-m (Figure 9).

Table 5. Lunar Trailblazer mission and flight system characteristics

Mission Parameters	
Volume, Mass	ESPA Grande, MEV 210 kg
Lifetime	2 years; launch to End of Primary Science Mission
Lunar Orbit	100 ±30km polar
Comm.	DSN compatibility
Subsystem	**Manufacturer/ Model**
CDH	Cobham Sphinx w/ custom mezzanine board
FSW	ASI MAX + LM DSE FSW
GNC	Blue Canyon Flexcore System
EPS	GomSpace Power Distribution, LM Arrays
Propulsion	Monoprop Hydrazine System
Telecom	SDL Iris radio / 4 LGAs, 1 MGA
Mechanisms	Honeybee SADA + SADE
Instruments	HVM^3 (JPL), LTM (Oxford)

Figure 9. The Lunar Trailblazer flight system shown deployed and packaged for launch



The design of the flight system heavily leverages commercial off-the-shelf (COTS) subsystems to achieve the mission requirements within the cost constraints (Table 5). The flight system shares many COTS elements with the Janus project, one of the other SIMPLEx missions, allowing personnel to leverage their experiences with the components on the two systems. The scalable suite of hardware subsystems enables the same low-cost spacecraft architecture to support both missions with a high degree of commonality, despite their disparate mission designs, environments, and science operations [Shoer et al., 2021]. A key difference is the propulsion system. Janus has electric propulsion. Lunar Trailblazer's hydrazine chemical propulsion system is derived from the hydrazine main engine and warm gas attitude control propulsion system on the 300-kg GRAIL spacecraft. Trailblazer's propulsion system provides ~1000 m/s of delta-v, enabling an efficient transit to the Moon and lunar orbit insertion.

5. OPERATIONS AND GROUND DATA SYSTEM

Caltech leads the mission operations and ground data system for Lunar Trailblazer with navigation and mission design provided by JPL. Mission operations and the ground data system are run by Caltech's Infrared Processing and Analysis Center (IPAC) and the science data system is run out of the Bruce Murray Memorial Laboratory for Planetary Visualization in Caltech's Geological and Planetary Sciences Division. IPAC has a four-decade history of space telescope instrument operations and ground data processing.

Lunar Trailblazer's science planning uses bespoke scripts, developed for Trailblazer. These scripts are based upon the uplink system for the Spitzer Space Telescope, as both missions have a deck of targets for planned observations. During the primary science phase, the team will plan science observations every two weeks, scheduling observations based on target visibility, favorable viewing geometries, and local times of day at the target site while managing the available data storage onboard the spacecraft and downlink data volume. Spacecraft and instrument commanding and housekeeping, health, and trending will leverage the open-source, multi-mission AMMOS Instrument Toolkit, developed by NASA.

Lunar Trailblazer will use Deep Space Network 34-meter antennas for uplink and downlink with an anticipated eight hours of DSN allocation per 24 hour period during the science phase.

An opportunity of the SIMPLEx program is greater participation of universities in mission operations. This will be the first planetary mission run from the Caltech campus.

6. Student Collaboration and Community Engagement

The Lunar Trailblazer mission team is dedicated to fostering the next generation of scientists and engineers who will become leaders in space exploration. When Lunar Trailblazer was selected, NASA also selected Lunar Trailblazer's Student Collaboration, an optional element of the SIMPLEx call. In addition to graduate students and postdoctoral scholars who will participate in the mission via the Co-Investigators, Lunar Trailblazer's Student Collaboration focuses on providing real-world experiences in space mission work to undergraduate students with a Caltech-Pasadena City College (PCC) partnership. Caltech is a small, top-five world-ranked research university with <1,000 undergraduates and ~1,300 graduate students. PCC is a nationally-recognized, regional 2-year college that is a Hispanic Serving Institution (HSI) with a diverse student body of >25,000 students and offers programs in areas directly related to the Lunar Trailblazer mission, e.g. Geology, GIS, Computer Programming, Applied Physics, Communications, and Web/Graphics Design. During the first two years of the project, we have provided 10-week to 2-year internship experiences to 22 undergraduates (13 PCC, 9 Caltech) in mission operations center systems, science communications, mission graphic design, geographic information systems, web design, science analysis, and science data processing.

Within the broader science community, Lunar Trailblazer makes regular presentations at science conferences (e.g., AGU, LPSC) and lunar community meetings focused on science and exploration (e.g., LEAG, NESF, ELS, LSIC, SSERVI). In October 2021, Lunar Trailblazer opened its target submission process to the community and hosted two mini-workshops, explaining how to create and submit lunar targets for acquisition by Lunar Trailblazer. Trailblazer has also focused on engagement and accessibility via public-facing communication activities: (i) intern-produced mission art (one picked up by space.com) and a web timeline of the history of discoveries regarding water on the Moon; (ii) past lunar datasets and Lunar Trailblazer's intended target deck, viewable in a web graphical user interface that allows users to navigate around the Moon, (iii) a "Trailblazer of the Week" feature that picks a team member from one of the Lunar Trailblazer partner institutions and describes their role on the mission (including all mission aspects: science, engineering, management, and contracting), their pathway to a STEM career, and their advice for those seeking to achieve a similar position. Lunar Trailblazer reports key milestones, mission events, and other outreach on its website (trailblazer.caltech.edu) and twitter (@lunartrailblazr).

7. Trailblazing Elements and Lessons Learned on a Pioneering Planetary Science SmallSat

Trailblazing Elements

Trailblazing elements of the Lunar Trailblazer mission include

- Collection of state-of-the-art datasets that enable future robotic and human missions to find and explore in situ lunar water at vastly lower price point than typical planetary missions
- Fully spatially co-registered mission data products delivered to the PDS to facilitate ready use by the community
- Majority early-/mid-career science team
- All-women mission leadership team (PI, DPI, PM)
- First planetary mission conducting operations from the Caltech campus
- Community college and undergraduate student staffing in mission operations
- The first handful of missions to pathfind the planetary rideshare match processes

Unexpected trailblazing elements include

- The first planetary science mission to implement uplink command encryption under NASA Standard 1006
- The first handful of missions to execute the new Class-D tailoring and review process for NASA
- Completely remote teamwork during spacecraft development from Systems Requirements Review through Critical Design Review and beyond (COVID-19 pandemic-induced)

Fitting in and Sizing the Smallsat Mission "Box"

Cost, schedule, and technical considerations drive design. Trailblazer's science approach is driven by some fundamental technical drivers (instrument maturity, communications, propulsion, power) as well as influenced by programmatic factors and implementation choices. Echoing the title of the National Academies report "Thinking Inside the Box", on CubeSat missions, a key question is what is the optimal size of the SIMPLEx small satellite mission "box", i.e. cost cap, risk posture, physical mass/volume, and ride procurement approach?

Rationale for Trailblazer's Science Approach—Doing "big science" with a small satellite requires judicious selection of science questions. For a body as well-studied as the Moon, simple imaging and fields measurements have mostly already been conducted. The "big science" is in specific data that advance understanding. The question of lunar water is both exciting ─ because of scientific mysteries as well as resource potential and high relevance to national plans for landed robotic and lunar exploration ─ as well as tractable within a small spacecraft's resources. As reviewed in Section 2, the main outstanding measurements essential to answer outstanding questions require: (1) different wavelength range coverage, (2) better spatial resolution in select locales, (3) better SNR for polar shadowed regions, and (4) systematically varied time coverage, but not full lunar spatial coverage.

The approach taken with Lunar Trailblazer is similar to that employed at Mars by the Mars Reconnaissance Orbiter instruments HiRISE and CRISM, i.e., acquisition of targeted very high resolution data at sites of known importance, covering <5% of the planetary body. As on Earth, all geographic locales on the Moon are not created equal in geologic science/exploration potential. From past data sets, we know some sites are important due to good exposure or unique/exemplary properties. Lunar Trailblazer's instruments will provide the highest spatial and spectral resolution visible/shortwave infrared and thermal data at the Moon, complementing Diviner and M^3 global datasets (Table 1). Lunar Trailblazer will target most polar PSRs thought to contain ice, follow up on key locales of distinctive lithology or anomalous water content identified in prior lunar datasets, and sample spatial variation driven by latitude (temperature) or soil maturity in more homogenous regions. This enables a several factor improvement in the spatial resolution of derived products mapping water, composition, and temperature for these key sites for science and exploration.

Importance of Prior Instrument Miniaturization Investment— Thanks to agency investments in instrument miniaturization for small satellites and landers in both the U.S. and U.K., there were mature, sufficiently low mass yet high spatial resolution infrared instruments available. Technology development and maturation efforts to reduce instrument mass and volume for landed missions and small satellites are essential for enabling "big science" in small satellites. Trailblazer's instruments are not inherently new, but the miniaturization relative to typical spacecraft instruments that might be >3x larger is quite significant, requiring substantial engineering. Lunar Trailblazer could not have been proposed without the prior technology development efforts to miniaturize its actively cooled shortwave infrared imaging spectrometer (NASA MatISSE; Ultra Compact Imaging Spectrometer, PI D. Blaney) or its multispectral thermal imager (UKSA TechDemoSat-1; Compact Modular Sounder, PI N. Bowles). Continued investment into instrument miniaturization is critical for future successful smallsat science missions.

Communications—Lunar Trailblazer's science implementation approach is also driven by pragmatic considerations: lightweight, high data rate communications systems are an area of ongoing technical development for small satellites. The Moon presently has no communications relay architecture, so each mission must bring their own system. Lunar Trailblazer's science instruments are capable of making a state-of-the-art global map of the Moon at full spatial resolution over the course of a few months, just like a Discovery or higher-class mission; however, downlink to Earth is Trailblazer's most fundamental limiting factor on total science return. At the time of proposal, Lunar Trailblazer was not certain it could afford or accommodate a more directional system. Hence, targeted science with 4 low-gain patch antennae was proposed (X-band IRIS radio and 4 LGA antennas, allowing a 256 kbps downlink rate) with a Phase A/B trade to examine higher capability. The outcome of the trade was an enhancement option, presented to NASA, to upgrade the radio and antennae (add 1 gimbaled MGA and an S-band transceiver) and supporting avionics boards and software for service as a 2-way communications relay for landed lunar assets as well as high downlink data rate (>5Mbps) for near-global Lunar Trailblazer data coverage. While the upgraded communications system was straightforwardly accommodated technically, it could not be accommodated within the project's budgeted reserves. An increase in project funding to execute the communications enhancement option was not greenlighted. The project since added a non-gimbaled MGA antenna, which could be accommodated in reserves; provided the project receives spectrum allocation, it may enable Trailblazer to achieve ~1.5 Mbps downlink rates. Lunar Trailblazer has no relay capability. A key lesson is that small satellite missions have inherently sharp inflection points in science per dollar relationships, though costs remain quite low in an absolute sense. Modestly higher cost caps and funding profiles or incentive structures for future planetary smallsat missions that allow an explicit ability for a PI to enumerate scientifically and programmatically desirable enhancement options as part of the call (including potential to involve stakeholders beyond NASA/SMD) would be a means to achieve science and exploration goals in a cost-efficient manner, maximizing small satellite potential.

Propulsion—Post-selection Lunar Trailblazer, had to switch spacecraft vendors, driven primarily by two factors. The electric propulsion system projected performance and its maturation schedule fell short of that expected at the time of the proposal. Additionally, an effort to utilize a commercial-off-the-shelf bus with a second modular bus hosting the instruments with cut-out for propulsion tanks resulted in mass inefficiencies and a spacecraft too heavy to meet the mission design constraints for a reasonable transfer time to the Moon. The design trade space could not close within the constraints of the mission's cost cap. Consequently, Lunar Trailblazer pivoted 4 months before its preliminary design review to Lockheed Martin Space and a chemical propulsion system. Although electric propulsion technologies offer significantly more propellant mass efficiency at the thruster level, for Trailblazer, the higher thrust of chemical propulsion allowed a lower total ΔV budget for a mission design to insert into lunar orbit. In select cases such as this, when considering both spacecraft and trajectory design, chemical propulsion can be overall more mass-efficient than electric propulsion. In Trailblazer's case, chemical propulsion enables a faster transfer into lunar orbit, reducing the overall mission duration and, therefore, the lifetime that system components must support. The hydrazine propulsion capability demonstrated by GRAIL and being utilized by Lunar Trailblazer can enable other SIMPLEx-class spacecraft of GRAIL/Lunar Trailblazer-class to reach many other science destinations [Shoer et al., 2021].

Power—After Communications, this is Trailblazer's second most limiting technical aspect. Upon the pivot from electric propulsion to chemical propulsion and a lower mass system, solar panel size needed to be reduced. This in turn drove a change in the HVM^3 electronics to a lower-mass, less-capable version. The ability to compress data was removed, resulting in a >4x increase in data downlink requirements for the same number of science images. Consequently, the project added a medium-gain antenna, which is expected to allow more margin in the number of science images relative to the minimum baseline. The project is also accepting power limits in time-of-day available to observe targets at certain solar geometries, a modest increase in target scheduling complexity for the ground team.

Programmatic Organizational Factors—Lunar Trailblazer is managed and reports through the Planetary Missions Project Office (PMPO) and Planetary Science Division (PSD), ultimately to the Division Director; however, the budgetary authority for Lunar Trailblazer rests with the Deputy Associate Administrator for the Exploration Science Mission Directorate who leads the Exploration Science and Systems Integration Office (ESSIO), which has no line of contact with the project. A lesson learned is that management and authority are best when integrated. This is particularly important when pursuing a new approach so that nimble programmatic responses and direct engagement of stakeholders enables clear communication lines that quickly and effectively respond to novel circumstances. Minimal organizational complexity and melded responsibility and authority are particularly beneficial for efficient interactions when teams on both project and stakeholder sides are small, as is the case for SIMPLEx missions like Lunar Trailblazer.

Finding a ride: project involvement with stakeholders is essential—A key aspect to enabling planetary science smallsats is access to space. High risk, fast missions like SIMPLEx need timely rides so that lessons learned can feed forward to aid future developments as well as future endeavors by personnel involved. Originally envisaged as a rideshare program, at the time of this writing, SIMPLEx is executing Janus as a rideshare on the Psyche launch and Escapade as a dedicated launch/rideshare acquisition. At the time of this writing, Lunar Trailblazer is baselined on IMAP (launching 2.5-years after Lunar Trailblazer flight system delivery), but NASA is conducting an action, set at the confirmation review, to investigate possibilities for an earlier ride. Close project-stakeholder communication on rides is essential as there are technical compatibility aspects (e.g., contamination control requirements, launch environments, trajectories and consequent delta-v needed), schedule aspects (availability of interface information, lifetime of components, storage effects), programmatic aspects (costs of acceleration of schedule or storage, interactions with launch providers and other manifested payloads, spectrum allocation), and risk posture implications (loss of key team members due to timings, launch vehicle readiness, consequences of slips). Timing of mission execution at certain destinations (e.g., the Moon and Mars) may also have programmatic implications for coordination of multiple missions so that data and operations lead to optimal programmatic science and exploration results across missions.

Implementing Class-D—The Class D tailoring approach allows realization of substantial cost savings in achieving priority science with modestly increased risk that is transparent to the project and all stakeholders. The approach is applicable, not only to small satellite secondary missions, but potentially to other mission types. A lesson learned is that tailoring is a continual process during development and requires continual application of Class-D principles to keep reporting and review requirements within programmatic scope.

8. SUMMARY

Lunar Trailblazer is a pioneering NASA SIMPLEx small satellite that will collect state-of-the-art science data on the form, distribution, and abundance of water on the Moon. Lunar Trailblazer is presently in implementation, on schedule and on budget for flight system delivery at the end of 2022. As one of the first generation of planetary science small satellites, the lessons learned in execution will feed forward to enabling small mission planetary science across the solar system.

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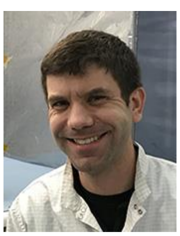

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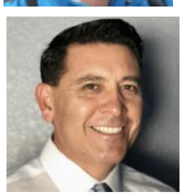

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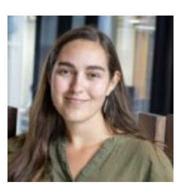

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