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Firefly Aerospace's Blue Ghost lunar lander snapped this shot of the moon from an altitude of about 62 miles (100 kilometers) on Feb. 24, 2025. (Image credit: Firefly Aerospace)

Lunar Surface Operations: On the Science Investigations of Blue Ghost-1 Payloads

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Abstract

This paper aims to investigate the characterization of Blue Ghost-1 Mission and the payloads deployed on the Moon's surface to justify in situ operations necessary for that characterization. The unique landing site Mare Crisium allows Firefly's payload partners to gather critical data about the Moon's regolith, geophysical characteristics, and the interaction of solar wind and Earth's magnetic field. Lunar Reconnaissance Orbiter (LRO) data have shown that basin Mare Crisium has particular relevance to the Moon that predict prominent Hall electric fields near lunar crustal magnetic fields and further suggest that the solar wind interplanetary magnetic field may reconnect with lunar crustal magnetic fields, most likely via electron-only reconnection [Sawyer et al. (2023)]. However, the payloads deployed require mitigation of environmental challenges that threaten the mission integrity. Several of the payloads are dedicated for the secondary objectives of the Mission.

Keywords. Magnetic reconnection, Lunar laser ranging, Magnetotellurics, Plume-surface interactions.

1. Introduction

Firefly's Blue Ghost Mission-1 (BGM1), named Ghost Riders in the Sky, launched on January 15th, completed its 45-day Earth to Moon transit allowing ample time to conduct health checks on each subsystem and begin payload science, ahead of landing on 2 March 2025. Touchdown on the Moon's surface was in a vast impact basin on the moon's near side, the side that faces Earth, called Mare Crisium (the Sea of Crises). Formerly an ancient asteroid impact site, *Mare Crisium* was created by volcanic eruptions that flooded the basin with basaltic lava about 3 billion years ago. Mare Crisium, a basalt plain that covers about 68,000 square miles of the moon, approximates the size of the U.S. state of Missouri. NASA reported, "It is the scar left behind when a massive asteroid impacted the Lunar surface several billion years ago, and the crater flooded with dark, igneous lava"[1]. Blue Ghost targeted a spot on a low volcanic dome called Mons Latreille inside the basin. The unique landing site allows Firefly's payload partners to gather critical data about the Moon's regolith, geophysical characteristics, and the interaction of solar wind and Earth's magnetic field. Scientists suspect the region is unique from the Apollo landing sites visited by astronauts in the late 1960s and early 1970s because of new discoveries anticipated about the moon's composition [2]. The payloads on Blue Ghost Mission-1 will help advance Lunar research and conduct several first-of-its-kind demonstrations, including testing regolith sample collections, Global Navigation Satellite System capabilities, radiation tolerant computing, and Lunar dust mitigation.

Mons Latreille, surrounded by mare lava flows, will serve as a landmark for Blue Ghost's *terrain relative navigation* software during the powered descent [3]. While rocks and regolith on the feature's flanks will not be directly accessible to the lander's instruments, its cameras will be able to image them.

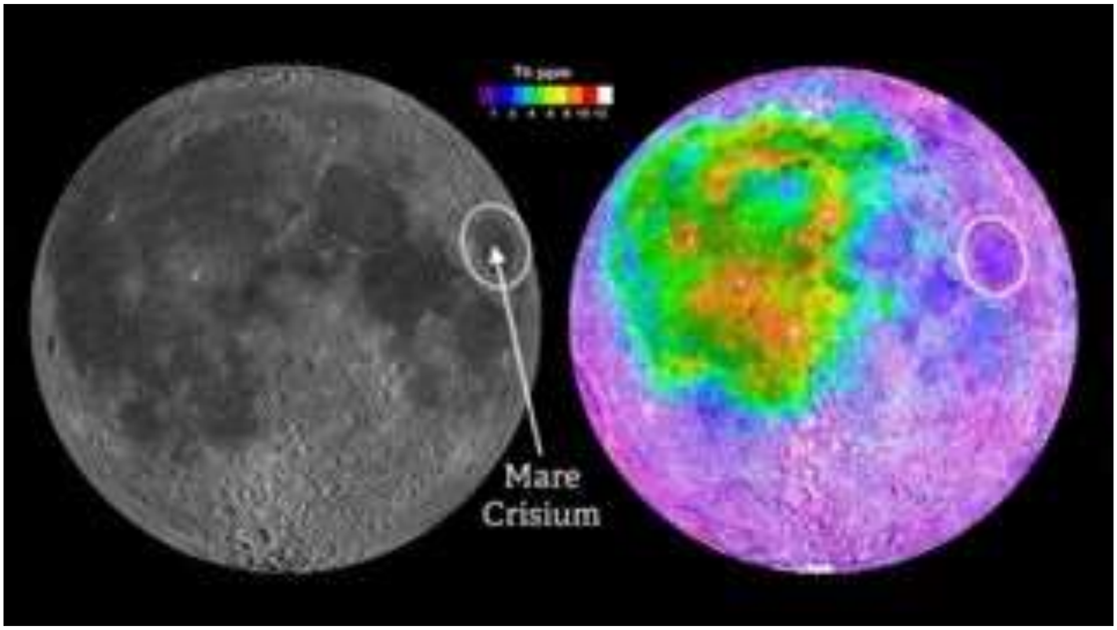

Figure 1. This NASA map shows the location of the vast impact basin Mare Crisium, or Sea of Crises, on the moon's Earth-facing near side Blue Ghost landing site. (Image credit: NASA).

Mons Latreille and the Connecting Ridge remain features of interest to the Lunar science community. The former is a Lunar cinder cone, while the latter is a remnant crustal block on the rim of the South Pole-Aitken Basin; neither has been explored in-situ. This knowledge gap will be closed with imagery collected by engineering cameras on the Blue Ghost. CLPS requirements state that each lander beyond the initial TO2 missions must include panoramic cameras to document the landing site. The panoramic cameras on the CLPS landers will image and be used to study rock abundance and texture, as well as the properties of the regolith excavated by the landers' descent engines. Similar investigations were performed by the stationary Surveyor landers [4].

The evolution of the Lunar magnetic field alludes to the Moon's interior structure, thermal history, and surface environment [5]. Both orbital- and in situ- observed magnetic data will indicate that the present-day Moon lacks a global magnetic field. Nonetheless, large-scale crustal magnetization with maximum local magnetic anomalies at the Lunar surface reaching hundreds of nanoteslas suggests the presence of a strong magnetic field in the past [6].

Firefly's Blue Ghost Lunar lander was loaded up with an MMH hypergolic propellant and MON-3 oxidizer to power the thrusters and main engine during transit from Earth to Moon. A narrow angle camera based on the Lunar Reconnaissance Orbiter Camera (LROC) was included on the orbital stage to enable landing site reconnaissance, supplementing BepiColombo's 3 m/pixel imaging capability with 1 m/pixel scale of the landing area from 100-km altitude. The Blue Ghost lander consisted of a box-shaped structural framework with two decks for mounting equipment and 155 kg of payload capacity, and four landing legs. Blue Ghost mission contained robust suites of science payloads selected through NASA Provided Lunar Payloads (NPLP) and the Lunar Surface Instrument and Technology Payloads (LSITP) programs [7]. Solar-powered panels mounted on the sides of the spacecraft or deploy-enabled to protrude above the top deck will provide 450 W nominal power and a peak 650 W. Communications at the surface should downlink an average of 6 Mbps, 10 Mbps peak, and uplink an average 0.2 kbps, 2 kbps peak [8].The Blue Ghost lander carried advanced instruments such as a regolith adherence characterization device, a lunar retroreflector for precision distance measurements, a radiation-tolerant computer, and thermal exploration probes, among other scientific payloads. The objectives for the mission are 1. investigate heat flow from the lunar interior, plume-surface interactions, crustal electric and magnetic fields, and 2. take X-ray images of the Earth's magnetosphere. Technology tests include regolith sampling, regolith adherence, Global Navigation Satellite System abilities, radiation tolerant computing, and dust mitigation using electrodynamic fields.

2. Discussion (of Blue Ghost Payloads)

Lunar GNSS Receiver Experiment (LuGRE)

Before GNSS usage can be embraced as a widespread and trusted solution for lunar position, navigation and timing, the capability must be proven and well understood at lunar distances. The Lunar GNSS Receiver Experiment (LuGRE) will provide flight data essential for this effort, capturing raw snapshot data and tracking GNSS signals at altitudes higher than have ever been achieved from both in-lunar orbit and on-lunar surface. The primary objectives of LuGRE are to 1) receive GNSS signals at the Moon, return data, and characterize the lunar GNSS signal environment; 2) demonstrate navigation and time estimation using GNSS data collected at the Moon; and 3) utilize collected data to support development of GNSS receivers specific to lunar operations. Science investigations in support of these guiding objectives have been defined, detailed, and prioritized to assist in development of the LuGRE science program.

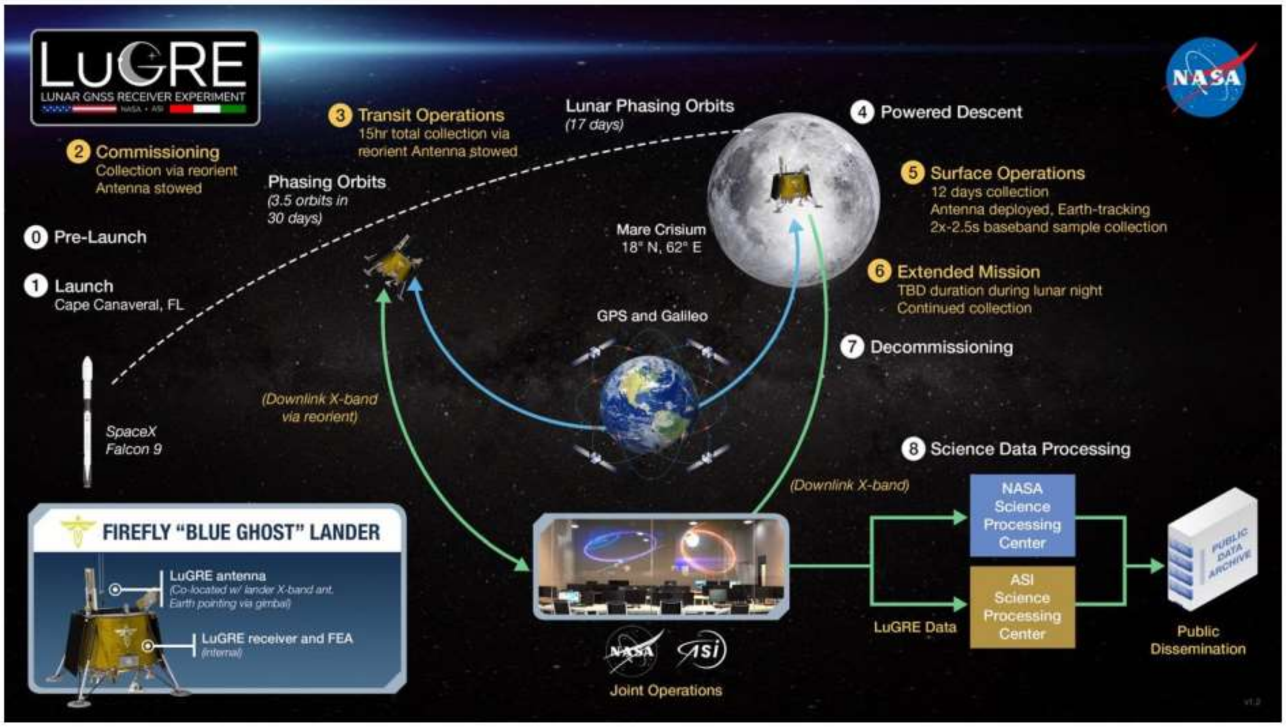

Figure 2.

Additionally, NASA navigation engineers from the Space Communications and Navigation (SCaN) program developed a navigation architecture providing accurate and robust Position, Navigation, and Timing (PNT) services for the Artemis missions. Global Navigation Satellite System (GNSS) signals used in high-Earth orbit and in lunar space aim to improve timing, enable precise and responsive maneuvers, reduce costs, and even allow for autonomous, onboard orbit and trajectory determination. Spacecraft near Earth have long relied on GNSS signals for PNT data [9]. In other words, spacecrafts in low-Earth orbits below about 1,800 miles in altitude can calculate their location using GNSS signals just as users on the ground might use their phones to navigate directional logistics. In the Lunar GNSS Receiver Experiment, fulfillment of the LuGRE science objectives will expand the proven reach of usable GNSS signals. Subsequent missions will be able to leverage LuGRE data and lessons learned by adding existing, proven, real-time navigation to operationalize GNSS for exploring the Moon. The primary goal of the LuGRE project is to extend GNSS-based navigation and timing to the Moon. As a technology demonstration payload on the BGM1 lunar lander, LuGRE will fulfill this goal by gathering and processing different types of GNSS data across several mission phases, codified in three overarching science objectives

- Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
- Demonstrate navigation and time estimation using GNSS data collected at the Moon.
- Utilize collected data to support development of GNSS receivers specific to lunar use [10].

LuGRE science investigations will be used to support the realization of future lunar GNSS investigations as summarized in the graphic shown in Figure 3 [11], categorized by processing level and increasing complexity, and ranked by priority (P1, P2, P3).

Figure 3. Science Investigations: Categorization and Prioritization

Next Generation Lunar Retroreflector

Lunar Laser Ranging (LLR) data represents a powerful tool to understand the dynamics of the Earth-Moon system and the deep Lunar interior. Over the past five decades ground station technology has significantly improved, whereas the lunar laser retroreflector arrays (LRAs) on the Lunar surface have not. The current instrumental LLR error budget is dominated by the spread of laser pulse returns due to the large size of the arrays. Next generation single solid lunar Cube Corner Retroreflectors (CCRs) of large optical diameter (whose LLR performance is unaffected by that time spread) aim to attain LLR accuracy below current centimeter values down to the desired millimeter level and much higher data collection rates [12]. In the 1970s, LLR measurements had a precision of a meter, then reached about 20 cm. Nowadays, after the upgrade ground station ranging capabilities by more than two orders of magnitude, old generation LRAs dominate the LLR error budget due to lunar librations, while LLR to single, large CCRs is unaffected by those librations (Figure 4). Currently, five sites have the most accurately known positions on the Moon that may serve as control points for lunar reference systems [13], including the one based on Lunar Reconnaissance Orbiter (LRO) data and metric maps; the future Lunar Geophysical Network (LGN); and positioning and navigation from orbiters equipped with laser time-of-flight capabilities. LLR will be one of the core technologies of the LGN mission [14] that contributes to the improved determination of the lunar interior structure.

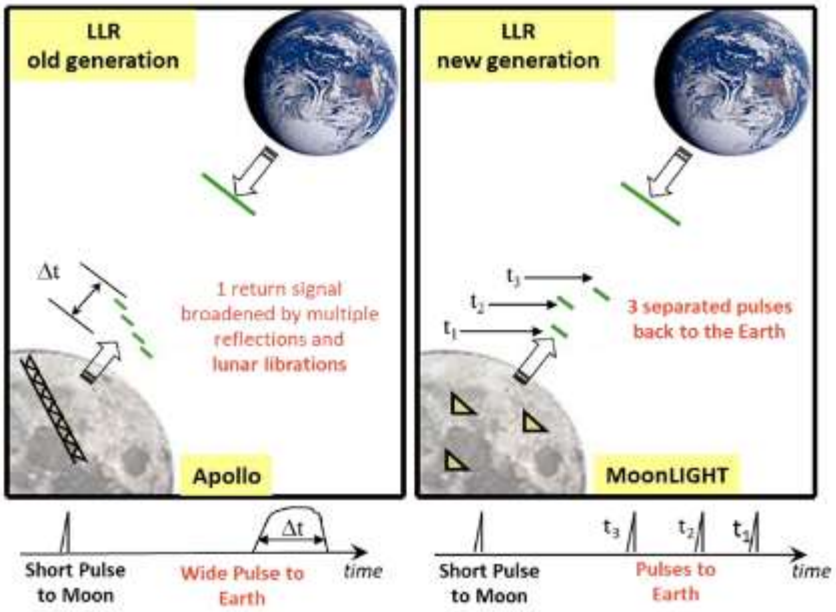

Figure 4 – Comparison between the broadening of the laser return pulse from old generation LRAs due to the libration tilt (left) vs separated laser return pulses from next-gen CCRs unaffected by lunar librations (right).

Further improvements will have a significant impact, enabling more refined ephemerides, improved tests of General Relativity (GR) and theories of relativistic gravity in the Sun-Earth-Moon system that furthers knowledge about properties of the lunar interior. LLR has finally proved a powerful tool to test gravity theories beyond GR, like spacetime torsion, through its potential manifestations in two-body systems like: Earth-Moon and Sun-Mercury [15] as well as Earth- LAser GEOdynamics Satellites (LAGEOS) [16].These gravity theories have been inspired by cosmological models' alternative [17] to dark matter and dark energy, explained by modifications to GR, and that may manifest in the solar system dynamics (and always in the weak-field, slow-motion regime).

Lunar Environment Heliospheric X-ray Imager

The process of magnetic reconnection at Earth's dayside magnetopause is recognized as the primary mechanism controlling the transfer of mass, momentum, and energy. This flow of energy fuels geomagnetic storms. The Lunar Environment heliospheric X-ray Imager (LEXI) is a wide field-of-view soft X-ray telescope developed to study solar wind-magnetosphere coupling [18]. It monitors the dayside magnetopause position and shape as a function of time by observing soft X-rays (0.1–2 keV) emitted from solar wind charge-exchange between exospheric neutrals and solar wind plasma in the dayside magnetosheath. Measurements of the shape and position of the magnetopause are used to test temporal models of meso-and macro-scale magnetic reconnection [19].

Payload-specific requirements prioritized potential landing areas within the mare. For example, Mare Crisium has bullseye magnetic anomalies on its northern and southern rims [20] which Lunar Magnetotelluric Sounder (LMS) monitors for optimum sensitivity to time-varying magnetic fields. In addition, the requirement for the landing site crust to be of relatively uniform thickness was prioritized for Lunar Magnetotelluric Sounder (LMS) and Lunar

Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER) data interpretation. These criteria first directed the mission to the central E-W corridor of the basin where the magnetic anomaly is lowest (Figure 5).

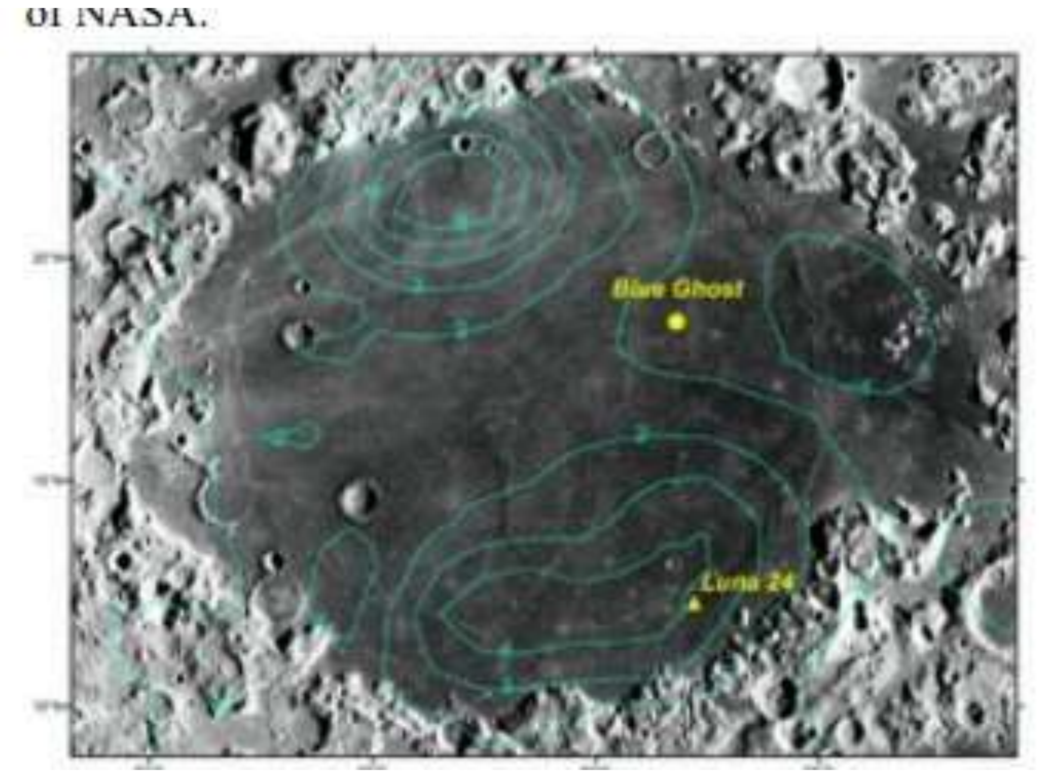

Figure 5. LROC Wide Angle Camera (WAC) mosaic of Mare Crisium. The yellow dot indicates the landing site selected for Blue Ghost. Magnetic anomaly contours (1 nT intervals) at 30-km altitude [21] are also shown.

The Lunar Environment heliophysics X-ray Imager (LEXI), also on the lander [22], preferred an eastern site for X-ray imaging of the interaction between the solar wind and Earth’s magnetosphere. Therefore, the mission focused on the east-central part of the basin in the vicinity of an old volcanic vent, which has recently been named Mons Latreille (Figure 6). This feature served as a good landmark for the terrain relative navigation capabilities of the spacecraft. A narrow angle camera was used during the orbital stage to enable landing site reconnaissance, supplementing BepiColombo Mercury Planetary Orbiter/Mercury Magnetosphere Orbiter’s 3m/pixel imaging capability with 1 m/pixel scale of the landing area from 100-km altitude.

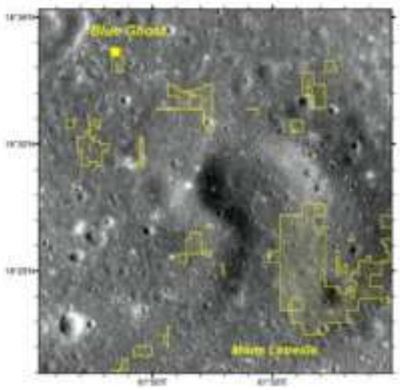

Figure 6. LROC WAC mosaic of the vicinity of the selected landing site (yellow dot). Yellow polygons delineate the areas of low rock concentrations based on an overlay analysis of Diviner rock abundance and Arecibo P- and S-band radar CPR (circular polarization ratio) images.

Lunar surface-based extreme ultra-violet (EUV) observations of the global terrestrial exosphere were imaged during Apollo 16 mission [23]. Anywhere an ion encounters a neutral atom, charge-exchange occurs. Within the heliosphere, flowing plasma in the solar wind routinely encounters environments of dense neutrals. Regions such as Earth's magnetosheath and cusps, collocate dense solar wind plasma with dense exospheric neutrals from Earth [24], displaying bright emitters of soft X-rays. The magnetopause boundary delineates a region of high solar wind density (magnetosheath) from one of low density (magnetosphere) [25]. The process of magnetic reconnection at Earth's dayside magnetopause is recognized as the primary mechanism controlling the transfer of mass, momentum, and energy. This flow of energy in turn is what fuels geomagnetic storms within Earth's magnetosphere, ionosphere, and thermosphere.

Lunar Magnetotelluric Sounder.

Magnetotellurics (MT) determines the resistivity structures using natural fluctuations in magnetic fields, which originate in the magnetosphere. The fluctuations induce a flow of electric current within conductive zones in the mantle. The fluctuations of the magnetic field occur over a wide frequency range. An MT system simultaneously measures the electrical field using grounded electrodes and high frequency induction-coil magnetometers. Natural variations in surface electric and magnetic fields enable calculations for how easily electricity flows in subsurface materials, which reveal their composition and structure [26].

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Developed by the Southwest Research Institute (SwRI), NASA's Lunar Magnetotelluric Sounder (LMS) will probe the interior of the Moon to depths of up to 700 miles, two-thirds of the way to the lunar center. The instrument will measure voltages across opposite pairs of electrodes. The magnetometer is deployed via an extendable mast to reduce interference from the lander. The magnetotelluric method will reveal a vertical profile of the electrical conductivity, providing insight into the temperature and composition of the penetrated materials in the lunar interior. [27].

Shortly after the successful landing of Firefly Aerospace's Blue Ghost lunar lander in the Mare Crisium region, four tethered Lunar Magnetotelluric Sounder (LMS) electrodes were deployed onto the lunar surface. In the video "NASA to Study the Moon's Interior**"** Robert Grimm, SWRI' s principal investigator for LMS, reports**,** "Signals sent from the solar wind have frequencies far below those of radio waves which take up to hours to complete a single cycle. These very low frequency signals that penetrate very deep into the Moon's interior permit correlation of both temperature and composition to be determined. Additionally, magnetic fields will be measured by a magnetometer.

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Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER)

During the Apollo program, heat flow measurements were considered among the high science priorities and were planned on four of the landing missions [28]. Lower heat-producing elements (HPEs) in the thorium-rich Mare Crisium crustal abundances that interact with underlying mantle materials to produce hybrid magmatism, lead to the magnesian suite of lunar rocks and possibly KREEP (potassium, rare-earth element and phosphorus) basalt [38]. Large-scale crustal magnetization with maximum local magnetic anomalies at the Lunar surface reaching hundreds of nanoteslas suggests the presence of a strong magnetic field in the past [29]. LISTER will measure the flow of heat originating from the interior of the Moon. Heat flow is obtained as a product of two separate measurements of thermal gradient and thermal conductivity of the regolith depth interval penetrated by a probe. The challenge here is to penetrate the probe deep enough to avoid the influence of insolation (i.e., solar effects) and measure the Moon's endogenic heat flow [30]. It is designed to penetrate 2- to 3-m depth into the Moon's rock and dust surface (the lunar regolith) and determine the heat flow as a product of two separate measurements: thermal gradient – how temperature changes with depth; and thermal conductivity – how well heat flows via conduction – at various depths using five measurements [31]. LGN, a long-lived next-generation network of surface geophysical stations, will provide simultaneous multipoint geophysical observations across four complementary disciplines: seismology, geodesy, heat flow, and electromagnetics from around the Moon. Together these observations will unlock key outstanding issues regarding the lunar interior including the existence of, size, and state of the inner core; the presence of a deep mantle partial melt layer; mantle thermal state; and composition including lateral and vertical heterogeneity [32].

Stereo Cameras for Lunar Plume-Surface Studies

An experiment to track and measure the transient phenomenon of plume-liberated regolith in near-vacuum conditions was performed in a dedicated plume-regolith facility housed at the University of Glasgow. Particle image velocimetry method was used to estimate the ejection velocity and ejected angle of regolith particles. Preliminary results captured ejecta development up to 30 ms from plume impingement. Flow visualization revealed the initial moments of plume boundary growth and regolith ejection. The vector images indicated a triangular-shaped sheet of particles sweeping from the regolith bed at a positive inclination with a local maximum velocity close to 100 m/s. And, the observed crater formation revealed the difference in cohesive forces between the selected simulants [33]. In the Physics Focused Ground Test (PFGT), NASA aimed to generate experimental data that could be used to predict lunar behavior of Plume-Surface Interactions [34]. The findings revealed the possible presence of wide, shallow craters in the Lunar environment [35]. The study explores the influence of background pressure, nozzle mass flow rate, and crater shape on the formation of ejecta tracks [36]. Payload stereo cameras specific to Lunar plume surface studies will enable NASA to reconstruct three-dimensional crater formation using a multiple camera photogrammetry system that will gather stereo images both during and after the Lunar lander's descent.

Following the initial moment of regolith ejection, a high inclination and high-velocity ejection occurred near the nozzle plume boundary at a time of around 8 ms. The dominance of the vertical component of velocity and the strongly inclined orientation of the vectors suggest that regolith particles have been ejected from a crater-like formation, possibly resulting from a bearing capacity failure of the regolith bed. Due to differences in particle flotation and cohesive properties, the lower-density particles entrained large amounts of particles, resulting in wide and deep craters with slanted walls. However, crater formation for the higher-density regolith was shallow and narrow, with steep walls observed at the end of the impingement. The difference in crater slope resulted in a steeper angle of ejection for higher-density particles which could directly interact with sensitive instruments close to the nozzle installation and potentially cause damage [37].

Lunar PlanetVac

Blue Ghost will not bring back any regolith samples; however, it will provide the first true demonstration of PlanetVac in space. An onboard laser and camera will each check how PlanetVac successfully transfers regolith samples probed and collected into the lander [38]. The lunar soil that PlanetVac collected will then be sorted by size, just as a future mission might do before taking scientific measurements.

PlanetVac, a revolutionary technology for acquiring and transferring regolith from almost any planetary body to instruments for in situ analysis [39], will employ a robust and dust tolerant pneumatic approach that is gravity agnostic (it can work in strong or no gravity field). PlanetVac also works with non-cohesive or cohesive materials (the latter materials have been the most difficult to deal with on prior missions, especially in low gravitational fields) [40]. The main advantage of the pneumatic transfer is that the point of acquisition and point of delivery can be anywhere on the spacecraft. Unlike scoops deployed by robotic arms which are constrained by the kinematic position of the arm and the location of instruments, pneumatic transfer lines can instead be routed around potential obstacles. As such, sample acquisition hardware can be placed best for sample acquisition, and instruments can be placed best for performing analysis.

Regolith Adherence Characterization

The interaction of Lunar dust and other environmental factors, like vacuum, temperatures, solar radiation, ultraviolet irradiation, and electron (e-) and proton (p+) irradiation with structures on the Moon and outside the future Gateway Lunar station may lead to permanent change or complete loss of thermal, optical, and other functionalities that could potentially lead to catastrophic failures. Among these factors, lunar regolith dust is the most aggressive, causing the main problem. Regolith Adherence Characterization (RAC) Payload mission will determine how lunar regolith dust sticks to a range of space materials and coatings (collected from NASA, academia, and industry) exposed to the Moon's environment at separate phases of flight caused by 1) landing and 2) during routine lander operations [41]. Active Lunar dust mitigation technologies (DMT) include electrodynamic dust shields to prevent the accumulation of dust on surfaces and remove dust already adhered to them; plasma discharging; utilization of an electron beam for surface cleaning; fluidal and mechanical methods; development of special brushes, etc. Passive DMT's include changing the surface properties of external materials in contact with the dust, using ion implantation, work function matching coatings; deposition of hard, scratch- and wear-resistant, variable transparency thin coatings with charge dissipative properties; laser patterned material surfaces (one type of, so called, multi-hierarchical surface structures); levelling coatings; ion beam textured surfaces (another type of multi-hierarchical surface structures), etc. In each of the approaches some of the surface properties are improved or changed to provide the dust mitigation effect. However, to achieve a full mitigation effect for dust and preserve all other properties of the surfaces like hardness, charge dissipation, thermal optical properties, etc., a novel approach Multifunctional Dust Mitigation Technology (MDMT) combines passive and active mitigation efforts [42]. A number of samples with dust mitigation properties were prepared and provided to Aegis Corporation for inclusion in the first unmanned NASA's RAC Payload experiment. The samples consisted of a Kapton 500HN space film, treated with a potential dust mitigation process and technology, providing a thin hard coating with charge-dissipative, scratch-resistant properties and an innovative static control white space paint with a proprietary fluorinated binder. The coated KaptonHN films are GEO space-qualified, spaceflight proven, and have a flight history in space antennas applications. They are space-qualified for the full range of Lunar temperatures and Lunar space environment conditions approximating to those in GEO. The influence of material and surface parameters like charge dissipation, surface work function, surface morphology, multi-hierarchical surface structures, etc. on the adhesion, accumulation and retention of the dust simulants will be studied and compared through optical image matching between the RAC Payload and ground experiments [43].

Electrodynamic Dust Shield

NASA's Commercial Lunar Payload System of Commercial Lunar Payload Services (CLPS) will fly an Electrodynamic Dust Shield (EDS) Payload as a technology demonstration to show the removal of dust from a glass panel as well as a thermal radiator surface. The EDS hardware being developed for this payload is based on EDS payloads flown on the International Space Station for NASA's Materials International Space Station Experiment (MISSE 11 and 15). The EDS payload consisting of the camera and EDS panels for the lens, the thermal radiator, and the glass EDS will be deposited on the ground by a deployable structure on the lander shortly after landing. The EDS will be released from a fifth leg of the lander and positioned directly onto the lunar surface to maximize dust contact. High resolution images will determine the dust removal efficiency of the EDS on the lunar surface [44] 19D.Science. NASA Science Payloads. Retrieved from science.nasa.gov] The camera will record dust deposition and removal on the Thermal Radiator EDS and the Glass EDS [45] Buhler, C. R. (2022, June). EDS to the Moon! In *Electrostatics Society of America*]. The technology makes use of electrostatic and dielectrophoretic forces to move charged dust particles off surfaces. A series of parallel electrodes connected to a multi-phase AC source generates a travelling wave that carries dust particles along. The Electrodynamic Dust Shield (EDS) operates on a physical principle which exploits traveling electrodynamic waves to wipe charged dust off a surface. The practical implementation of the physical principle is conducted by fabricating an EDS composed of a rigid or flexible insulating substrate, a specific number of electrodes according to the chosen configuration, and a dielectric capping. The dielectric coating prevents short circuits and electrical breakdowns and ensures safe operations [44]. Technology makes it possible to create a non-uniform electric field on a surface that needs to be removed from dust. The influence of electricity weakens the electrostatic adhesion of dust particles, resulting in an active dust mitigation effect [47] NASA Is Preparing To Test An Electric Anti-Dust Shield on The Moon's Surface in 2024. (1 May, 2024). Retrieved from www.orbitaltoday.com. By exposing lunar dust to a multiphase low frequency alternating current discharge, dust can be removed from important elements of the lander module, solar panels, or even spacesuit.

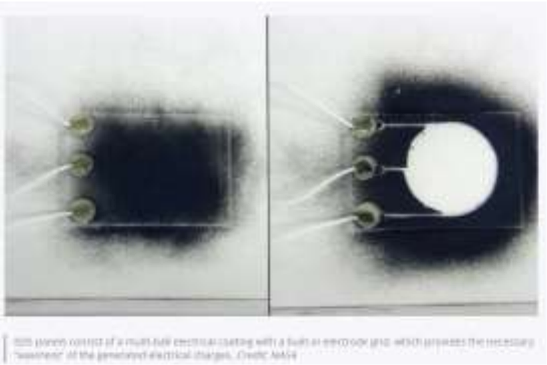

Figure 7.

Initially tested on Earth in vacuum chambers at the Surface Physics Laboratory, a working prototype was finally delivered to the ISS in 2019 as part of NASA's Materials International Space Station Experiment (MISSE).

Operating since 2001, MISSE has already tested over 4,000 materials and other technological solutions for conducting extraterrestrial activity [48]. Since the Moon's surface is in direct contact with the interplanetary medium, the interaction of the Moon with the solar wind plasma flowing from the Sun forms a unique plasma physics laboratory. Moreover, the absence of a significant ionosphere on the Moon should enable low-frequency radio astronomy to be carried out, particularly from the farside of the Moon where radio interference from terrestrial sources should be absent. [49] National Academies of Sciences, Engineering, and Medicine. 2007. The Scientific Context for Exploration of the Moon. Washington, DC: The National Academies Press.].

Radiation Tolerant Computer System

"RadPC-Lunar" a conceptual technology demonstration of a novel computer architecture that can recover from faults caused by ionizing radiation. RadPC-Lunar, was selected by NASA in 2019 through its Commercial Lunar Payload Services (CLPS) project to spend a minimum of 7-days in the Mare Crisium [50] Major, C., LaMeres, B., Klumpar, D., Springer, L., Sample, J., Tamke, S., ... & Davis, J. (2021, March). Overview of the upcoming radpc-lunar mission. In *2021 IEEE Aerospace Conference (50100)* (pp. 1-7). IEEE]. Technology will demonstrate increased reliability over the state-of-the-art space computers during in-situ resource utilization, robotic surface operations, and entry/descent/landing maneuverers. Second, it will characterize radiation effects from the environment of the lunar surface and track upsets within the computing fabric for the purpose of correlating them to data from on-board dosimeters. RadPC will demonstrate its ability to scrub and reconfigure components of its architecture that experience damage from faults induced by space radiation. Three Teledyne dosimeters will be deployed in a separate experiment within the same payload to characterize the radiation environment. During its time spent in transit to and on the lunar surface, RadPC-Lunar will demonstrate the ability for a computer architecture to continue performance and commit repairs on a system compromised by a harsh radiation environment. The payload will also provide a unique set of measurements on the ionizing radiation environment as it passes through the Earth's magnetosphere during transit to the Moon. Though the experiment is expected to run for a minimum week on the Lunar surface, all subsystems are intended to run during transit time from Earth to the Moon. A diagram of the various components of the RadPC payload is shown in Figure 8 below.

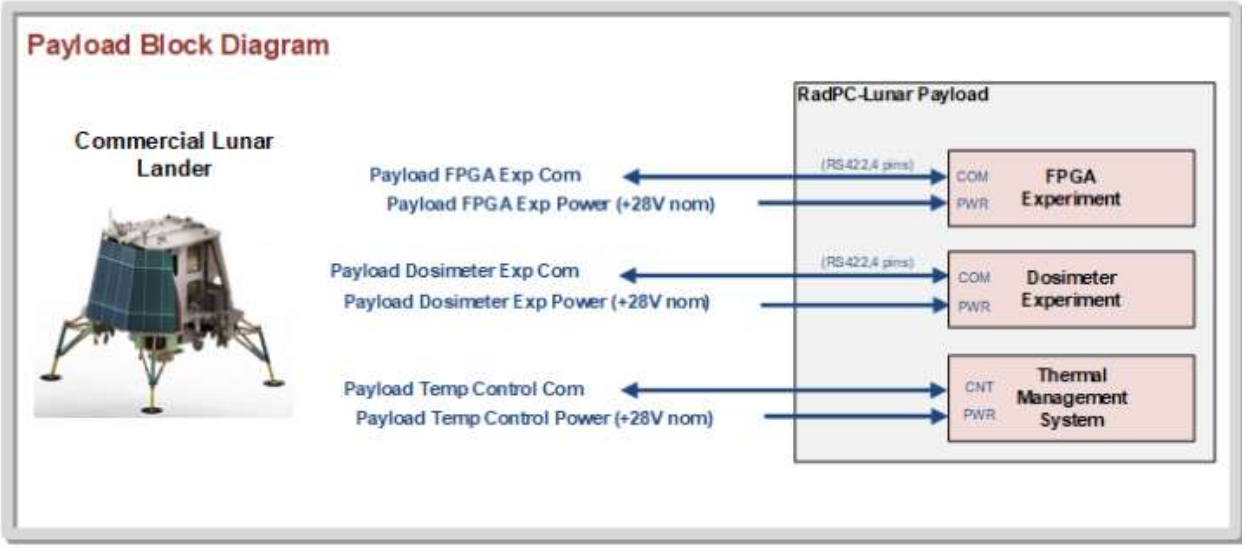

Figure 8. Payload Concept for RadPC-Lunar payload

The thermal management system will keep the temperatures of RadPC and the dosimeters consistent. As
The lunar surface fluctuates between extremes of cold and heat, a heating element within the payload will activate during cold to raise the temperature to desired levels. When heat needs to be released, the payload will radiate the excess away from the experiments. The consistency in temperatures allows for smoother performance of the RadPC architecture and dosimeters with no significant power draw from the lander.

5. Conclusion

High priority lunar surface objectives are dependent on navigation to sites of interest identified from remotely sensed data. Lunar Reconnaissance Orbiter (LRO) data have shown that basin Mare Crisium has particular relevance to the Moon's that predict prominent Hall electric fields near lunar crustal magnetic fields and further suggest that the solar wind interplanetary magnetic field may reconnect with lunar crustal magnetic fields, most likely via electron-only reconnection (Sawyer et al. (2023). Does magnetic reconnection occur in the Near Lunar surface environment? *Geophysical Research Letters 50*(16)). Geothermal heat flux of the Moon is believed to vary primarily due to the distribution of radiogenic materials both spatially and vertically through the lunar crust (Siegler et al. (2022). Lunar heat flow: Global predictions and reduced heat flux. *Journal of Geophysical Research: Planets*, *127*(9)). Navigating LEXI, LISTER, and LMS payloads to these specific areas to extract samples of these unique mafic materials will enable astronauts to map a region, contextualize their observations and use in situ analytical instrumentation that may further suggest such reconnections. Data collected will depend on the reliable integrity of payloads Radiation Tolerant Computer System, EDS, Lunar PlanetVac, Regolith Adherence Characterization employed for the observations and collections.

References

[1] Wilcox, K. (22 January 2025). CLPS mission heads for vast basalt plain. Retrieved from aww.appel.nasa.gov

[2] Malik, T. (2 March 2025). What time will the private Blue Ghost probe land on the moon today? How to watch live. Retrieved from www.space.com

[3] Nagihara S. et al. (2022). Landing site selected for the Blue Ghost Mission to Mare Crisium. *53rd Lunar Planetary Society Conference*, Abstract #1390.

[4] Shoemaker, E., Batson, R., Holt, H., Morris, E., Rennilson, J., & Whitaker, E. (1969). Observations of the lunar regolith and the Earth from the television camera on Surveyor 7. *Journal of Geophysical Research*, *74*(25), 6081-6119.

[5] Cai, I. et al. (2025). Persistent but weak magnetic field at the Moon's midstage revealed by Chang'e-5 basalt. *Science Advances 11*(1)**.**

[6] Dyal, P., Parkin, C., & Daily, W. (1974). Magnetism and the interior of the Moon. *Rev. Geophys. 12*, 568–591.

[7] Schonfeld, J. (2023, October). Summary of the contracted deliveries of NASA payloads to the moon via commercial lunar payload services (CLPS). In *2023 IEEE International Conference on Systems, Man, and Cybernetics (SMC)* (pp. 863-866). IEEE.

[8] Williams, D. (2 March, (2025). Blue Ghost Mission 1 (Firefly). *NASA Space Science Data Coordinated Archive*.

[9] Konitzer, L., Parker, J., Ashman, B., Esantsi, N., Facchinetti, C., Dovis, F., ... & Impresario, G. (2024, September). Science Objectives and Investigations for the Lunar GNSS Receiver Experiment (LuGRE). In *Proceedings of the 37th International Technical Meeting of the Satellite Division of The Institute of Navigation* (*ION GNSS*),1061-1081).

[10] Konitzer, L., Parker, J., Ashman, B., Esantsi, N., Facchinetti, C., Dovis, F., ... & Impresario, G. (2024, September). Science Objectives and Investigations for the Lunar GNSS Receiver Experiment (LuGRE). In *Proceedings of the 37th International Technical Meeting of the Satellite Division of The Institute of Navigation* (*ION GNSS*),1061-1081).

[11] Konitzer, L., Parker, J., Ashman, B., Esantsi, N., Facchinetti, C., Dovis, F., ... & Impresario, G. (2024, September). Science Objectives and Investigations for the Lunar GNSS Receiver Experiment (LuGRE). In *Proceedings of the 37th International Technical Meeting of the Satellite Division of The Institute of Navigation* (*ION GNSS*),1061-1081).

[12] Nagihara, S., Banks, M. E., Grimm, R. E., Stillman, D. E., Watkins, R. N., & Ghent, R. R. (2022, March). Landing Site Selected for the Blue Ghost Mission to Mare Crisium. In *53rd Lunar and Planetary Science Conference* (Vol. 2678, p. 1390).

[13] Porcelli, L., Currie, D. G., Muccino, M., Dell'Agnello, S., Wellnitz, D., Villoresi, P., ... & Kopeikin, S. (2021, December). Next generation lunar laser retroreflectors for fundamental physics and lunar science. In *Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032*.

[14] Wagner, et al. (2017). Coordinates of anthropogenic features on the Moon. *Icarus, 283*, 92.

[15] Haviland, H., Weber, R., Neal, C., Lognonné, P., Garcia, R., Schmerr, N., ... & Bremner, P. (2022). The lunar geophysical network landing sites science rationale. *The Planetary Science Journal*, *3*(2), 40.

[16] March, R., et al. (2011). Constraining spacetime torsion with the Moon and Mercury. *Phys. Rev. D, 83*, 104008.

[16] March, R., et al. (2011) Constraining spacetime torsion with LAGEOS**.** *Gen. Relativ. Grav., 43*, 3099-3126.

[17] Damour, T., Piazza, F., & Veneziano, G. (2002). Violations of the equivalence principle in a dilaton-runaway scenario. *Phys. Rev. D, 66*, 046007.

[18] Walsh, B., Kuntz, K., Busk, S., Cameron, T., Chornay, D., Chuchra, A., ... & Winkert, G. (2024). The lunar environment heliophysics X-ray imager (LEXI) mission. *Space Science Reviews*, *220*(4), 37.

[19] Walsh, B., Kuntz, K., Busk, S., Cameron, T., Chornay, D., Chuchra, A., ... & Winkert, G. (2024). The lunar environment heliophysics X-ray imager (LEXI) mission. *Space Science Reviews*, *220*(4), 37.

[20] Baek, S., Kim, K., Garrick-Bethell, I., & Jin, H. (2019). Magnetic anomalies within the Crisium basin: Magnetization directions, source depths, and ages. *Journal of Geophysical Research: Planets*, *124*(2), 223-242.

[21] Tsunakawa, H., Takahashi, F., Shimizu, H., Shibuya, H., & Matsushima, M. (2014). Regional mapping of the lunar magnetic anomalies at the surface: Method and its application to strong and weak magnetic anomaly regions. *Icarus*, *228*, 35-53.

[22] Banks M., et al. (2022). Landing site selected for the Blue Ghost mission to Mare Crisium. *53rd Lunar and Planetary Science Conference,* 1390.

[23] Carruthers, G., Page, T., & Meier, R. (1976). Apollo 16 Lyman alpha imagery of the hydrogen geocorona.

Journal of Geophysical Research, *81*(10), 1664-1672.

[24] Walsh, B. M., Niehof, J., Collier, M. R., Welling, D. T., Sibeck, D. G., Mozer, F. S., ... & Kuntz, K. D. (2016). Density variations in the Earth's magnetospheric cusps. *Journal of Geophysical Research: Space Physics*, *121*(3), 2131-2142.

[25] Ng, J., Walsh, B., Chen, L. J., & Omelchenko, Y. (2023). Soft x-ray imaging of Earth's dayside magnetosheath and cusps using hybrid simulations. *Geophysical Research Letters*, *50*(10), e2023GL103347.

[26] Grimm, R. E. (2013, March). Low-frequency electromagnetic methods for planetary subsurface exploration. In *2013 IEEE Aerospace Conference* (pp. 1-9). IEEE.

[27] Gran, R. (2025). *NASA Instrument on Firefly's Blue Ghost Lander to Study Lunar Interior*.

[28] Langseth, M., Keihm, S., & Peters, K. (1976). Lunar heat-flow values. In: Lunar Science Conference, 7th, Houston, Tex., March 15-19, 1976, Proceedings. Volume 3. (A77-34651 15-91) New York, Pergamon Press, Inc., 1976, p. 3143-3171.

[29] Jollif, B. et al. (2000). Major lunar crustal terranes: Surface expressions and crust-mantle origins. *Journal of Geophysical Research 105*(E2), 4197-4216.

[30] Dyal, P., Parkin, C., & Daily, W. (1974). Magnetism and the interior of the Moon. *Rev. Geophys.* **12**, 568–591.

[31] Nagihara, S., Zacny, K., Ngo, P., Sanasarian, L., Zasadzien, M., Wang, A., ... & Knorr, J. (2023, October). Robotic measurements of heat flow planned in Mare Crisium (2024) and the Schrödinger basin (2025) of the Moon. In *AAS/Division for Planetary Sciences Meeting Abstracts# 55* (Vol. 55, No. 8, pp. 319-06).

[31] Neal, C. & Weber, R. (2022, August). The lunar geophysical network mission. In *Lunar Reference System Working Group*.

[32] Bremner, M. The Lunar Geophysical Network Landing Sites Science Rationale. *The Planetary Science Journal*.

[33] Subramanian, S., Wilson, A., White, C., Kontis, K., Evans, D., & Van den Eynde, J. (2024). Tracking plume-regolith interactions in near-vacuum conditions. *Physics of Fluids*, *36*(1)]

[34] Eberhart, C., West, J., & Korzun, A. (2022). Overview of plume-surface interaction data from subscale inert gas testing at NASA MSFC test stand 300 vacuum facilities. *AIAA Paper No. 2022-1811*

[35] Rubio, J., Gorman,M., Diaz-Lopez, M., & Ni, R. (2022). Plume-surface interaction physics focused ground test 1: Setup and preliminary results. *AIAA Paper No. 2022-1810.*

[36] Rubio, J., Gorman,M., Diaz-Lopez, M., & Ni, R. (2022). Plume-surface interaction physics focused ground test 1: Setup and preliminary results. *AIAA Paper No. 2022-1810*

[37] Subramanian, S., Wilson, A., White, C., Kontis, K., Evans, D., & Van den Eynde, J. (2024). Tracking plume-regolith interactions in near-vacuum conditions. *Physics of Fluids*, *36*(1).

[38] Stahl, A. (12 December 2024). Tech funded by Planetary Society launches to the Moon next month. *The Planetary Society***.**

[39] Zacny, K., Lorenz, R., Rehnmark, F., Costa, T., Sparta, J., Sanigepalli, V, ... & Hovik, W. (2019, March). Application of pneumatics in delivering samples to instruments on planetary missions. In *2019 IEEE Aerospace Conference* (pp. 1-13). IEEE.

[40] Fitzgerald, Z., Zacny, K., Mueller, R., Morrison, P., McCormick, M., Wang, A., ... & Dupuis, M. (2022). PlanetVac: Sample Acquisition and Delivery System for Instruments and Sample Return. In *53rd Lunar and Planetary Science Conference* (Vol. 2678, p. 2586).

[41] Kleiman, J., Iskanderova, Z., Krishtein, L., Ng, R., & Sodhi, R. (2023, August). Regolith adherence characterization (RAC) experiment on the Moon and it's ground-based simulation: Materials Issues. In *IOP Conference Series: Materials Science and Engineering 1287*(1), 012040. IOP Publishing.

[42] Kleiman, J., Iskanderova, Z., Krishtein, L., Ng, R., & Sodhi, R. (2023, August). Regolith adherence characterization (RAC) experiment on the Moon and it's ground-based simulation: Materials Issues. In *IOP Conference Series: Materials Science and Engineering 1287*(1), 012040. IOP Publishing.

[43] Kleiman, J., Iskanderova, Z., Krishtein, L., Ng, R., & Sodhi, R. (2023, August). Regolith adherence characterization (RAC) experiment on the Moon and it's ground-based simulation: Materials Issues. In *IOP Conference Series: Materials Science and Engineering 1287*(1), 012040. IOP Publishing

[44] *19D.Science. NASA Science Payloads*. Retrieved from science.nasa.gov.

[45] Buhler, C. R. (2022, June). EDS to the Moon! In *Electrostatics Society of America*] [44] 19D.Science. NASA Science Payloads. Retrieved from science.nasa.gov

[46] Scifoni, L. (2024). *Trade Space Analysis and Optimizing of Rigid Electrodynamic Dust Shields for Lunar Dust Mitigation* (Doctoral dissertation, Georgia Institute of Technology.

[47] *NASA is preparing to test an Electric Anti-Dust Shield on the Moon's surface in 2024*. (1 May, 2024). Retrieved from www.orbitaltoday.com.

[48] Scifoni, L. (2024). *Trade Space Analysis and Optimizing of Rigid Electrodynamic Dust Shields for Lunar Dust Mitigation* (Doctoral dissertation, Georgia Institute of Technology).

[49] National Academies of Sciences, Engineering, and Medicine. 2007. The Scientific Context for Exploration of the Moon. Washington, DC: \ The National Academies Press.

[50] Major, C., LaMeres, B., Klumpar, D., Springer, L., Sample, J., Tamke, S., ... & Davis, J. (2021, March). Overview of the upcoming radpc-lunar mission. In *2021 IEEE Aerospace Conference (50100)* (pp. 1-7). IEEE]. [49] National Academies of Sciences, Engineering, and Medicine. 2007. The Scientific Context for Exploration of the Moon. Washington, DC: The National Academies Press.

Appendix 1.

The IM-2 landing site is just 0.5 degrees from the geographical south pole of the Moon. It is located on the Connecting Ridge, which Spudis et al. (2008) interpreted as a pre-Nectarian crustal massif sculpted by overlapping impacts [Spudis P. D. et al. (2008) Geophys. Res. Lett., 35, L14201.]. The regional geology is dominated by ejecta from Shackleton Crater, which is 8 km from the landing site. The site is situated amongst the small craters Marston, Wild, and Cheetam, which were previously evaluated as candidate field stations for Artemis astronauts [Scoville Z. C. (2022) LPSC LIII, Abstract #1079] and which will be explored by the IM-2 Micro-Nova hopper [Martin T. D. et al. (2023) LPSC LIII, Abstract #2007]. The following geologic questions can be addressed at Connecting Ridge:

1. Is pure anorthosite present? Kaguya Spectral Profiler data suggest the presence of pure anorthosite (PAN; >98% plagioclase) in Shackleton Crater's ejecta blanket [Yamamoto S. et al. (2012) Geophys. Res. Lett., 39, 13]. PAN is likely a metamorphic lithology which is not represented in the lunar sample suite. High-albedo boulders on the Connecting Ridge have been identified as candidate PAN deposits [Bernhardt H. et al. (2022) Icarus, 379, 114963]. If IM2 observes white rocks with an interlocking crystalline texture, it would support this interpretation.
2. Is polar regolith coarse-grained?
   Polarimetry data indicate that regolith at high latitudes might have a larger average grain size than at the equator [Jeong M. et al. (2015) Astrophysical Journal Supplement Series, 221, 16]. Individual particle sizes can only be measured through sample return. However, close-up imaging of the lander footpads could determine whether this general trend for regolith grain size holds true.
3. Do local breccias contain any candidate clasts from the mantle?
   In addition to PAN, impact melt breccias are likely common in the heavily-cratered southern circumpolar region. It is estimated that 20- 40% of the material in these breccias are South PoleAitken Basin (SPA) ejecta [Moriarty D. P. and Petro N. E. (2024) JGR Planets, 129, 4], which could include material which was exhumed from the lunar mantle. If this lithology is olivine-rich, it would have a readilyidentifiable green color [Yamamoto S. et al. (2012) Nature Geosci., 3, 533-536]. If, on the other hand, it is pyroxene-rich [Melosh H. J. et al. (2017) Geology, 45, 1063-1066], it might be more difficult to distinguish mantle material from impact melt and igneous clasts (e.g. from the floor of Amundsen Crater).

Appendix 2. Ten NASA payloads onboard Blue Ghost weigh about 330 pounds (150 kilograms).

Payload	Function
Next Generation Lunar Retroreflector	Reflective target for pulses shot from Earth-based Lunar Laser Ranging Observatories to measure the distance between Earth and the moon within the sub-millimeter range. Lunar Laser Ranging (LLR) data represent a powerful tool to understand the dynamics of the Earth-Moon system and the deep lunar interior. Over the past five decades, the ground station technology has significantly improved, whereas the lunar laser retroreflector arrays (LRAs) on the lunar surface did not. Current instrumental LLR error budget is dominated by the spread of the returning laser pulse due to the large size of the arrays. Next-generation single solid lunar Cube Corner Retroreflectors (CCRs) of large optical diameter (whose LLR performance is unaffected by that time spread) aim to fully exploit the current laser ranging station capabilities to attain LLR accuracy below current centimeter value down to the desired millimeter level and much higher data collection rates.
Regolith Adherence Characterization	Experiment containing 30 different types of material surfaces for post-landing exposure to the moon's environment in order to determine surface effects resulting from the lunar environment and dust.
Lunar Environment Heliospheric X-ray Imager (LEXI)	An experiment to monitor the interaction of solar wind with Earth's magnetosphere, and how energy in that environment generates geomagnetic storms.
Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER)	A small drill expected to cut up to 9 feet (3 meters) below the lunar surface to measure the moon's heat flow at different depths.
Electrodynamic Dust Shield	A tech demonstration payload to test how electric fields can manipulate lunar dust on the moon's surface.
Radiation Tolerant Computer System	A tech demonstration to test a potential radiation hardness method for computer protection against the harsh radiation environment in space and on the moon.
Lunar Magnetotelluric Sounder	Instrument to enable calculations for lunar electrical conductivity per monitoring interactions between the solar wind and Earth's magnetic field.
Lunar PlanetVac	Vacuum-like device to collect lunar dust samples with a pneumatic system powered by compressed gas.
Stereo Cameras for Lunar Plume-Surface Studies	Cameras to record images of the moon during the lander's descent showing how the probe's thruster plume kicks up dust during touchdown.
Lunar GNSS Receiver Experiment (LuGRE)	**A** navigation system experiment that will attempt to use Earth's own guidance and navigation satellite system (GNSS) for spacecraft tracking around the moon.