

Firefly Blue Ghost Mission 1: SCALPSS 1.1 Payload and Mission Overview

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The Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) 1.1 payload collected first-of-its-kind calibrated stereo imagery during the transit, descent, landing, and 14-day surface mission of the Firefly Aerospace Blue Ghost Mission 1 (BGM1) lander in early 2025. The payload, which was manifested on BGM1 in early 2021 and delivered to the provider in late 2022, included commercial off-the-shelf and “build-to-print” hardware with previous flight heritage. This included six cameras, which utilized three types of lenses optimized for both pre- and post-landing measurements with the stereo photogrammetry technique. The payload performed several image captures during lunar transit, including during a lunar orbit insertion burn and while in low-lunar orbit. During descent and landing on March 2, 2025, the payload acquired and transferred to the lander approximately 1800 images, which captured several key phenomena of interest to the plume-surface interaction topic. During the subsequent 14-day

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surface mission, several thousand additional images were collected and transferred to ground; these images were post-processed to produce high dynamic range images of the post-landing terrain as the lunar day progressed. The stereo photogrammetry technique is applied to the images to produce three-dimensional shape measurements of the lunar terrain, and is expected to provide an assessment of plume-induced erosion from the powered landing, which will inform modeling and predictive efforts for future landings at the Moon, Mars, and elsewhere.

I. Introduction

Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) is a NASA lunar science payload that has flown to the Moon on two Commercial Lunar Payload Services (CLPS) flights to-date. SCALPSS is the first purposely-designed measurement system to collect images during the descent and landing of a spacecraft, capturing interactions between the landing vehicle's exhaust plume and the destination's surface.

Previous space missions to the Moon, Mars, and asteroids have captured plume-surface interactions during or after relevant spacecraft operations, but these observations have usually been incidental, limiting quantitative analysis. A camera aboard Surveyor 5 captured a post-landing plume-surface interaction experiment using one of the vernier engines, which was analyzed to estimate eroded volume using before and after images of plume-induced cratering [1]. Eroded mass from Apollo missions has been estimated via analysis of ejecta in descent video [2] and photographs of the surface beneath the lander taken by crew [3]. More recently, imagery from the Lunar Reconnaissance Orbiter has been used to estimate surface terrain changes from the Chang'e-3 landing site [4]. At Mars, erosion under the Phoenix spacecraft was estimated from post-landing images using spacecraft dimensions as a reference [5], a digital elevation map (DEM) of the post-landing surface beneath the InSight lander was reconstructed using images taken from an arm-mounted camera ("pseudo-stereo" photogrammetry) [6], and descent video was taken during the Mars Science Laboratory and Mars2020 landing events, which was used to determine onset altitude [7]. The OSIRIS-REx spacecraft captured on camera the descent and excavation of a crater during sampling operations at the asteroid Bennu [8].

The SCALPSS payload aboard Firefly's Blue Ghost lander acquired first-of-its-kind calibrated stereo imagery of spacecraft plume-surface interactions. The images returned from the payload are then processed using the stereo photogrammetry technique to extract spatial and depth information about the images, namely the three-dimensional erosion profiles of the regolith which were caused by the lander's descent engines. The effects induced by propulsive descent onto an unimproved/unaltered planetary surface can include surface erosion and formation of an ejecta sheet containing a high-speed particle-laden flow. For powered landings at the Moon and Mars, these effects may pose risks such as obscuration of the landing site and damage to the landing vehicle or nearby assets [9]. Understanding these effects and improving predictive modeling capabilities is a priority in the Artemis era as humanity seeks to establish a renewed and permanent lunar presence [10].

A variety of low size, weight, power, and cost science payloads have been developed by NASA and its partners in recent years for CLPS flight opportunities on small robotic landers, which are developed by commercial aerospace companies contracted to deliver them to the lunar surface through the CLPS initiative. The SCALPSS project was formed in late 2018 at NASA Langley Research Center in response to a call for payloads to be manifested on the first CLPS contracted flights (Intuitive Machines Mission 1 and Blue Ghost Mission 1). The original concept was to develop a low-cost payload that could be developed and tested in a very short period of time, by relying on heritage from previous payloads and commercial off-the-shelf hardware. The first SCALPSS project, which utilized heritage flight-qualified hardware from the Mars2020 Entry, Descent, and Landing Cameras (EDLCam) [11], was proposed in 2018 as a CLPS measurement system to quantify surface erosion during powered landings. The first SCALPSS payload, referred to herein as SCALPSS 1.0, was manifested to the Intuitive Machines 1 (IM-1, CLPS Task Order 2-IM) "Nova-C" lander mission in 2019. The payload comprised four commercially-available cameras (Teledyne FLIR® Chameleon3 CM3-U3-31S4M-CS) with short focal length lenses (Peau Productions® GP33728, 3.37 mm), a Data Storage Unit (DSU) originally developed by the Jet Propulsion Laboratory (JPL), which was "built-to-print" at NASA Langley Research Center (LaRC), and a Smartronix® Universal Serial Bus (USB) Hub. The hardware was purchased off-the-shelf and ruggedized/qualified for spaceflight operations at NASA LaRC.

The NASA LaRC SCALPSS 1.0 team delivered the payload to Intuitive Machines, Inc. in early 2021 and it was integrated onto the Nova-C lander several months later. The lander launched from Cape Canaveral on a SpaceX® Falcon 9 rocket on February 15, 2024, arriving at the Malapert A region of the lunar South Pole on February 22, 2024. The lander experienced an off-nominal descent trajectory which prevented updated altitude data from being streamed to

the payloads on board, preventing SCALPSS from powering on and triggering image acquisition during the descent sequence. The Nova-C ultimately came to rest on the lunar surface on its side, resulting in limited command and data uplink/downlink throughout the following 7-day surface operations. SCALPSS 1.0 successfully completed in-transit functional tests and operated from the lunar surface, showing that all hardware survived the launch, lunar transit, and landing and operated as expected, but was not able to acquire or downlink full resolution imagery during the landing sequence, nor did it capture a clear view of the eroded landing site after touchdown due to off-nominal lander events.

The second iteration of the payload, called SCALPSS 1.1, was assigned to the Firefly Aerospace Blue Ghost Mission 1 (BGM1, CLPS Task Order 19D) flight in early 2021. This iteration included the same DSU and USB Hub, with the same camera model, but featured an additional two cameras to collect additional pre-plume-surface interaction stereo images, increasing the total number of cameras from four to six, and utilized two new lens types. This paper provides an overview of the SCALPSS 1.1 system and its operations throughout the successful BGM1.

II. Payload Development Overview

The Blue Ghost lander featured a central main engine used for transit maneuvers and early descent, and four pairs of smaller, reaction control system (RCS) thrusters which were used for the terminal descent. This meant that rather than one centralized region of plume-surface interaction beneath the lander, there were potentially eight regions (grouped into four pairs) of erosion to be captured by the cameras. As a result, a variety of lens types and camera configurations were considered in the hardware down-selection process. An added objective for SCALPSS 1.1 was to measure, with sufficient (≈ 2 mm) depth accuracy, the landing site before plume-surface interaction occurred. This was intended to allow a more comprehensive before-and-after measurement of the surface and accurate estimation of total volume of erosion. Ultimately, the six-camera SCALPSS 1.1 system was split into groups: two long focal length (LFL) cameras and four short focal length (SFL) cameras. The camera model selected was the same one used for the four-camera SCALPSS 1.0 system, which featured a monochrome, 3.2-megapixel, 2048×1536 pixel resolution CMOS sensor ($3.45 \mu\text{m}$ pixel size) with a $1/1.8''$ format (P/N CM3-U3-31S4M-CS). The specifications for the camera model are listed in Table 1. The sensor model is capable of up to 12-bit dynamic range images, but 8-bit images were used to conserve payload data volume transfer from the lander to the ground in flight. The 8-bit flight images were compressed using JPEG with a quality level of 98 to conserve data volume within the amount allocated for lander downlink. The LFL cameras were fitted with a 50 mm focal length lens (Schneider[®] Xenoplan 50 mm) and focused to a distance corresponding to a lander altitude of approximately 10 m. The lenses and target altitudes selected for the LFL cameras were based on predictions for (a) the photogrammetric accuracy of the system and (b) the expected “onset” of significant erosion obtained from pre-flight computational fluid dynamics (CFD) predictions. The size of the stereo overlap between the two cameras at this altitude with the selected focal length would not be able to view the entire ≈ 3 m diameter area of interest within which most erosion was expected, so the LFL camera pair was oriented to prioritize viewing of one of the four expected regions of plume impingement, beneath the ‘north’-facing pair of RCS thrusters. The four SFL cameras were positioned to have optimal stereo overlap and photogrammetric accuracy at an altitude of 0 m (after touchdown). Due to the large area of interest desired for measuring erosion from the four pairs of RCS thrusters, two SFL cameras were fitted with 3.37 mm lenses (the same model used for SCALPSS 1.0, Peau Productions GP33728) to view most of the area beneath the vehicle. The other two SFL cameras were equipped with 5.4 mm lenses (Peau Productions GP54025) to obtain a slightly higher resolution view of the ‘north’ pair of RCS plume impingement regions. For more information on the SCALPSS 1.1 camera configuration, see Refs. [12, 13].

After down-selecting the lenses and optimizing the locations and orientations of the cameras, the SCALPSS 1.1 configuration was completed, and design of the structural mounting hardware began. Custom camera brackets were designed to hold the cameras in their desired poses and secure them to the bottom deck of the vehicle. Four brackets were designed for the six-camera system, with the LFL0/SFL0 and LFL1/SFL1 cameras co-located on two combination brackets, and the SFL2 and SFL3 cameras each located on their own single bracket. The reason for the combination brackets was to ensure a sufficiently accurate exterior orientation calibration could be performed for the LFL camera pair despite the long focal distance and narrow field-of-view. A relative orientation could be performed between the LFL camera and SFL camera with which it shared a bracket, and then the exterior orientation for the LFL camera pair could be deduced from the exterior orientation for the SFL pair, which was performed during calibration at Firefly’s facility after payload integration. The reader is referred to the accompanying paper by Fahringer et al. [13] for more details of the camera calibration process. Figure 1 shows a photograph of the four SCALPSS 1.1 camera brackets with the six cameras and lenses attached, and the DSU and USB Hub assembled for vibration testing.

Table 1 Summary of the specifications used for the SCALPSS cameras on BGM1.

Parameter	Specification
Camera P/N	Teledyne FLIR® Chameleon3 CM3-U3-31S4M-CS
Sensor	Sony® IMX265 Monochrome
Megapixels	3.2
Pixel Size	3.45 μm
Resolution	2048 $\times$ 1536
Sensor Type	CMOS
Sensor Format	1/1.8"
Pixel Bit Depth	8

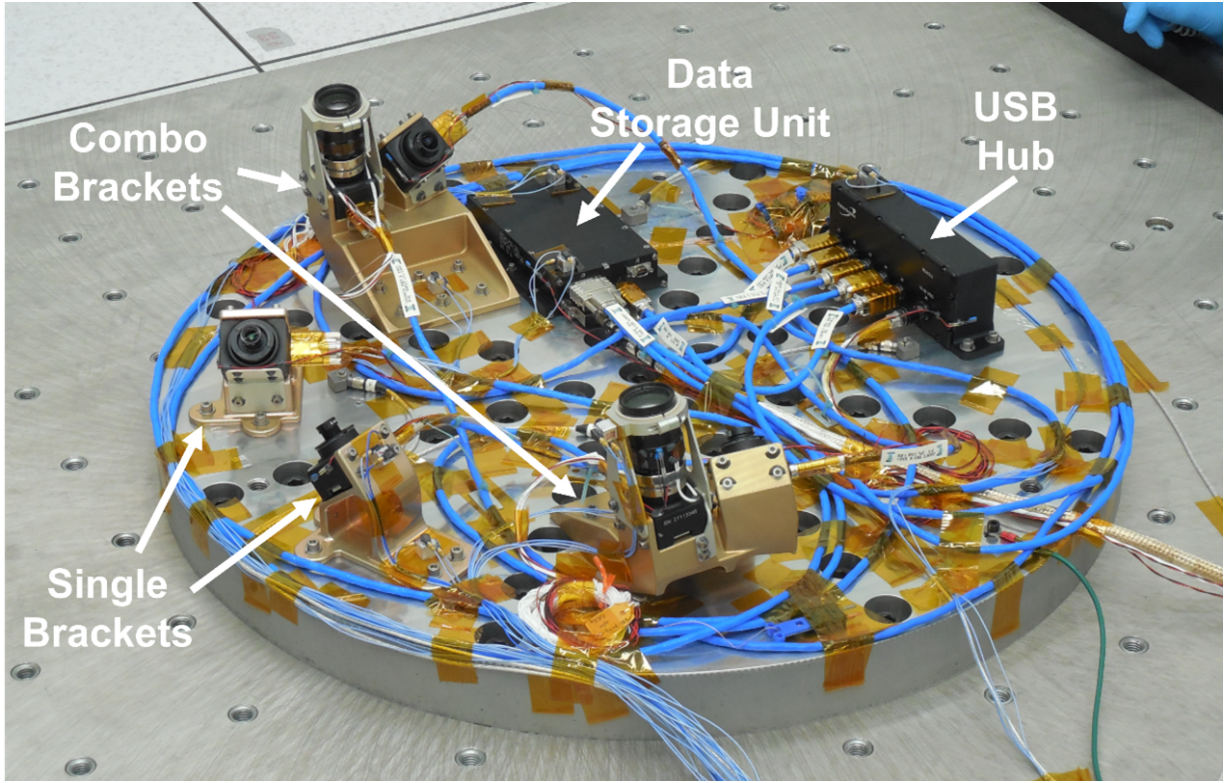


Fig. 1 SCALPSS 1.1 flight payload assembled on vibration test stand.

After fabrication of the flight brackets, fabrication of the harnessing, and ruggedization of the hardware, the SCALPSS 1.1 flight payload was assembled. Following assembly, the payload was subjected to three phases of environmental testing: Electromagnetic Interference/Compatibility, Vibration, and Thermal/Vacuum. All three tests were carried out in facilities at NASA LaRC within the Systems Integration and Test Branch. The payload was operated before, during, and after each environmental test to ensure both survivability and operability at relevant flight levels. After completion of environmental testing, the system was delivered to Firefly Aerospace in October 2022. The payload was mechanically and electrically integrated to the Blue Ghost lander in February/March 2024. Functional tests prior to installation and post integration were performed to verify functionality after each configuration change. Calibration was performed on the payload in June 2024. The Blue Ghost lander underwent its own full environmental testing with all the fully integrated and operational NASA payloads prior to shipment to the launch site at Cape Canaveral. SCALPSS was operated several times throughout this process in its flight configuration to ensure operational readiness.

III. Blue Ghost Mission Overview

The Blue Ghost lander launched on a SpaceX Falcon 9 rocket from Cape Canaveral on January 15, 2025. The 45-day transit included several orbits around the Earth before trans-lunar injection and lunar orbit insertion. During transit, a total of four checkout operations were performed by SCALPSS. Each transit checkout involved acquiring a sequence of images, transferring low-resolution thumbnails to the lander, and downlinking those thumbnails to Earth for verification of expected payload performance. Each transit checkout operation was performed autonomously through pre-programmed flight software; however, the Firefly team also allowed some manual commanding of the payload after each checkout to obtain full-resolution images from the six cameras as data downlink bandwidth permitted. The payload was also thermally monitored during each checkout and throughout the entire transit and flight mission. A summary of the SCALPSS transit operations is shown in Table 2. The Blue Ghost performed a lunar orbit insertion burn maneuver on February 24, 2025; during this operation the SCALPSS payload performed ad-hoc image acquisition to capture a sequence of images of the pulsed RCS jet burn. Two of the four SFL cameras clearly captured emission from one pair of plumes, while the other two SFL cameras captured full-resolution imagery of the lunar surface.

Table 2 Summary of the transit image captures performed by SCALPSS during BGM1.

Checkout Name	Date of Capture [UTC]	Images Acquired/Downlinked
Transit Checkout #1	January 15, 2025	12 thumbnails, 6 full-resolution
Transit Checkout #2	January 18, 2025	12 thumbnails, 6 full-resolution
Transit Checkout #3	January 31, 2025	12 thumbnails, 6 full-resolution
Lunar Orbit Insertion Burn Capture	February 24, 2025	12 thumbnails, 832 full-resolution
Low Lunar Orbit Checkout	March 2, 2025	12 thumbnails

A few hours after the low lunar orbit checkout operation, the lander began deorbit, descent, and landing. The Blue Ghost touched down in Mare Crisium at approximately 08:34 UTC on Sunday, March 2, 2025. The SCALPSS payload successfully collected a total of 1,818 images during the descent sequence according to the descent concept of operations implemented in the flight software. The LFL cameras acquired images at 10 frames per second from a vertical range of 50 meters to 5.5 meters above ground level as relayed by real-time altimetry from the Blue Ghost to the SCALPSS DSU. The four SFL cameras acquired images at 8 frames per second starting from 30 meters above ground level and continued until 10 seconds after touchdown (TD) was signaled from the Blue Ghost to the DSU. During the descent and landing phase, the cameras were operated in an auto-ranging mode which allowed for automatic adjustment of the camera exposures from 17 μ s to 10 ms and a gain adjustment from 0 to 20 dB. The cameras were configured such that the auto-exposure ranged to find the optimal value first, then if additional signal was needed, the gain was increased. The images were also set to have a gamma of 2 (corresponding to a gamma compression value γ of 1/2 according to traditional definition). Each camera image packet which was transferred from the SCALPSS DSU to the Blue Ghost and then downlinked to Earth was parsed using ground software into (a) a processed JPEG image and (b) a metadata log file containing the camera's exposure and gain values for that particular frame, in addition to several other parameters including timing and synchronization information. After TD+10 seconds, the SFL cameras transitioned to surface mode operations, where they collected sequences of high dynamic range (HDR) images at fixed exposures (0.25, 2.0, 16.0, and 128.0 ms) and a gain setting of zero. Using post-processing algorithms described in [14], the four 8-bit low dynamic range (LDR) images were synthesized into a single HDR image which enabled visualization of terrain features with dramatically different signal intensities (owing to the harsh illumination in the lunar environment). For an example of four LDR images and the synthesized resulting HDR image, see Fig. 1 in Ref. [14]. The surface mode captures were pre-programmed to acquire in the following sequence immediately post-landing: one capture every 10 seconds for one minute, then every 1 minute for 10 minutes, then every 10 minutes for the first 60 minutes, after which point the payload performed a capture every hour. The payload was powered off as needed to conserve power and allow for other payload operations to consume more available power. Once powered back on, SCALPSS would automatically perform a surface capture and transfer the images to the lander if more than an hour had elapsed since the preceding capture. SCALPSS continued performing hourly captures for the first 61 hours post-landing. During the first several hours after lander surface commissioning, the descent imagery transferred from the DSU to the lander and then downlinked to Earth, where it was parsed into images by the ground software. The descent images reveal first-of-its kind, high-resolution imagery of several phenomena of interest, including: onset of plume-surface interaction, formation of ejecta "streaks,"

visual obscuration of the landing site, ejection of regolith particles and larger rocks, complex interactions between the multiple pulsed RCS jets and their ejecta, and finally, touchdown and dust settling. The accompanying paper by Weisberger et al. [15] contains detailed analysis of the LFL camera descent imagery, and the paper by Danehy et al. [16] contains qualitative descriptions and detailed analysis of the SFL camera descent imagery.

During the first days of the surface mission, several ad-hoc image captures were performed during and around other NASA payload operations to monitor performance and alterations to the landing surface. These other payload operations included, but are not limited to, the Electrodynamic Dust Shield (EDS) [17], Lunar Planetary Vacuum (LPV), and Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER) [18]. On March 4, 2025 the SCALPSS payload was powered off for an extended period of time due to high surface temperatures. The payload remained powered off for nearly ten Earth days as the Sun traversed through lunar noon and temperatures began to decrease. On March 13, 2025, SCALPSS was successfully powered back on and resumed hourly image captures as lander resources permitted. SCALPSS captured images during the end umbra of the lunar eclipse on March 14, 2025. As the lunar sunset approached, the SCALPSS team adjusted the HDR exposure settings to the following bracketed exposures: [8.0 ms, 8.0 ms, 128.0 ms, 128.0 ms]. These repeated exposure values were chosen in an effort to observe potential dust lofting from electrostatic charging changes during sunset and to maximize image signal in the diminishing ambient light. These settings were used with HDR captures every 10 minutes during sunset, with the final SCALPSS surface capture occurring at approximately 21:06 UTC on March 16, 2025. The SCALPSS payload was powered off shortly after. In total, 159 image captures were performed by SCALPSS during the surface portion of the mission, with most of them being HDR captures. Table 3 provides a summary of the three mission phases of BGM1, including their start/end dates and SCALPSS camera groups and corresponding capture numbers.

Table 3 Summary of SCALPSS image captures for each of the three mission phases during BGM1.

Mission Phase	Start Phase	End Phase	Camera Group	Capture Number(s)
Transit	January 15, 2025	March 2, 2025	LFL	0-3
			SFL	0-4
Descent	March 2, 2025	March 2, 2025	LFL	4
			SFL	5
Surface	March 2, 2025	March 16, 2025	LFL	–
			SFL	6-165

IV. Ongoing and Future Work

Analysis of the SCALPSS 1.1 imagery is ongoing. The primary science results of the payload are introduced in an accompanying paper by Tyrrell et al. [14]. Future publications will expand on these results with imaging and analysis from each phase of the Blue Ghost mission, including transit checkouts, the lunar orbit insertion burn, descent, touchdown, post-landing HDR, and post-landing auto-expose surface captures. They will also discuss the insights gleaned from the successful Blue Ghost Mission 1, which will impact future flight instrumentation development efforts for in-situ measurements. Results from the SCALPSS 1.1 imagery and analysis will be valuable in validating and improving predictive modeling capabilities for lunar landing environments. SCALPSS data from BGM1 will be made available on the Planetary Data System in early 2026 [19].

SCALPSS hardware is and will be used to support future flight and ground test applications. The SCALPSS 1.X system will be flown once more on the upcoming Blue Origin MK1 Pathfinder/Blue Moon demo mission to the lunar south pole region. An updated version, SCALPSS 2.0, will be manifested on Blue Ghost Mission 4. Lessons learned during the payload development, operations, and post-mission analysis are being incorporated into these future instrument and payload development efforts. The SCALPSS 2.0 system will feature a custom-built Mini-Suite Electronics (MSE) avionics system, new camera models for improved resolution and/or stereo coverage, and active [20, 21] and/or passive [22] illumination via laser and reflector elements. The addition of the illumination elements are intended to enable ejecta sheet tracking and velocity measurements, as well as illumination in shadowed regions of the terrain which are expected at the lunar south pole. Currently, a SCALPSS-GT (Ground Test) system, which contains some of these newly added elements, has been integrated in the 60-ft vacuum sphere at NASA LaRC to support the Human Landing Systems (HLS) Plume-Surface Interaction Ground Test [23].

Acknowledgments

The authors wish to acknowledge the Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) project, which is funded by NASA's Space Technology Mission Directorate Game Changing Development program. The authors wish to recognize NASA Marshall Space Flight Center's Manish Mehta as an early plume-surface interaction collaborator on the original SCALPSS concept. Down-selection of the lenses used and the altitudes targeted in the LFL camera design were informed by preliminary CFD predictions performed by members of the Fluid Mechanics Branch at NASA Marshall Space Flight Center, including Jeffrey West, William Krolick, and Andrew Weaver. The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

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