

Firefly Blue Ghost Mission 1: SCALPSS 1.1 Post-Landing Terrain Measurements

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Images of the lunar surface were taken by the Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) payload on board the Firefly Aerospace Blue Ghost lander, which successfully completed its first mission in March 2025. Stereo photogrammetry was applied to these images to measure the three-dimensional post-landing terrain. The terrain measurement was obtained from synthesized high dynamic range (HDR) images from multiple captures taken throughout the first 37 hours of the 14-day lunar surface mission. Four of the six possible stereo pair combinations from the four short focal length (SFL) camera views were used to identify image points spread across the stereo overlap regions. These regions covered much of the terrain beneath the lander but were highly concentrated around one of the four pairs of reaction control system (RCS) thrusters. A custom post-processing workflow was applied to extract features from the images using both manual and semi-automated feature detection and correlation methods. The points were then combined and triangulated to produce a depth map, or digital elevation map (DEM), containing thousands of spatial $[X, Y, Z]$ coordinates, computed in the lander's reference frame and describing the post-landing lunar terrain. The results presented comprise the first dedicated in-situ measurements for plume-surface interaction at the lunar surface. A discussion of the SCALPSS surface imagery, data processing methods, post-landing terrain measurement results, and a summary of ongoing efforts towards a comprehensive plume-induced erosion measurement are presented.

I. Introduction

In March 2025, the Firefly Aerospace Blue Ghost Mission 1 (BGM1) lander touched down in the Mare Crisium region of the Moon carrying a suite of NASA science instruments. The Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) payload was one of the instruments on board. The payload collected data during descent, landing, and throughout the 2-week surface mission. The primary science objective of this SCALPSS system (labeled as SCALPSS 1.1, [1, 2]) was to measure the 3D shape of the lunar surface beneath the landed vehicle using the stereo photogrammetry technique. The reconstructed shape of the terrain is expected to enable an estimation of the erosion induced by the lander plumes, an important parameter for predictive modeling of plume-surface interactions (PSI) for powered landings on the Moon and Mars [3, 4]. The Blue Ghost lander featured eight reaction control system (RCS) jets grouped in four pairs distributed around the lander, which were pulsed during terminal descent. For a more detailed overview of the SCALPSS 1.1 payload configuration and summary of BGM1, the reader is referred to the accompanying paper by Maddock et al. [5]. This paper presents the first post-landing terrain measurement using the four short focal length (SFL) SCALPSS camera images collected in high dynamic range (HDR) mode after the landing. Section II presents an overview of the SCALPSS surface imagery and timeline of images used for the initial measurements. Section III provides a brief description of the data processing methods used to extract spatial measurements from the images. Section IV presents the post-landing terrain estimate, and finally, Section V presents conclusions and a summary of ongoing and future efforts.

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II. Surface Imagery

The SCALPSS payload entered surface mode operations 10 seconds after touchdown on March 2, 2025, at the conclusion of the descent image capture. After this point, the four SCALPSS SFL cameras (indexed as SFL0, SFL1, SFL2, and SFL3) began regular captures at fixed, pre-selected exposures and zero gain. Each sequence included four different exposure values of 0.25, 2.0, 16.0, and 128.0 ms. The fixed exposures were selected to bracket the estimated range of intensities that could be detected in the harsh lunar illumination conditions using the 8-bit cameras. HDR images are created by combining the four low dynamic range (LDR) images in the following steps. The LDR images are first background subtracted, such that the dark current (15 counts) is removed, then fed into MATLAB®'s `makehdr` function along with the relative exposures, minimum counts (10), and maximum counts (239) creating the initial HDR image. A gamma correction is then applied using MATLAB's `imadjust` function with `gamma` set to 2. Finally, composite images can be viewed using the `tonemap` function in MATLAB, which compresses the HDR image such that it can be viewed on an LDR display. An example of four LDR images taken with bracketed exposures is shown for the SFL1 camera in Fig. 1a. In Fig. 1b, the resultant HDR image is shown. These images were taken on March 3, 2025, the day after the lander touched down.

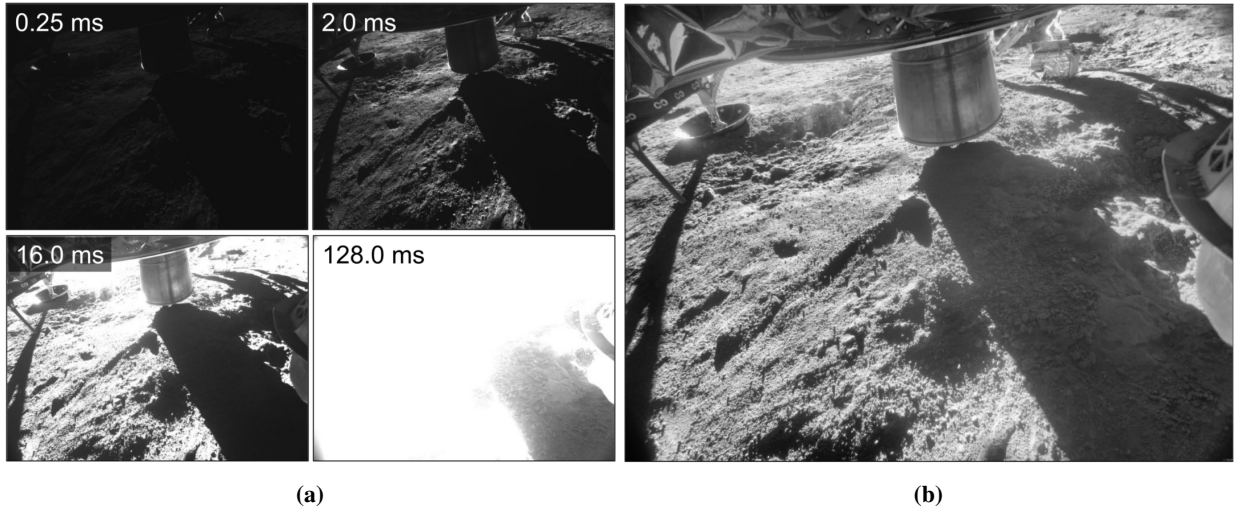


Fig. 1 (a) Fixed-exposure images and (b) composite HDR image for the SFL1 camera, taken during surface operations on March 3, 2025.

The composite HDR images for the first surface mode capture, referred to as Cap6 (because it was the sixth SFL capture of the mission) are shown in Fig. 2. The images generally appear hazy, with the SFL0 image in particular being highly obscured from dust adherence to the lens. Furthermore, at the time of landing (approximately 08:34 UTC), the solar elevation angle was $\approx 3.4^\circ$ above the horizon, so much of the terrain was cast in shadow. The solar azimuth angle was $\approx 91.6^\circ$, corresponding to the east direction (as estimated by the Jet Propulsion Laboratory's Horizons program [6]). In the first several hours of the surface mission, other science payloads on board began operations; some of these payloads were deployed to the surface. The increasing illumination of the surface and gradual removal of dust over time, from gravity or perturbation from other payload operations, improved the quality of the resultant SCALPSS HDR images. The SFL0 camera lens, however, remained substantially coated in dust. The images taken during this time on SFL0, though hazy, still contain some surface features and can be used for stereo processing with enhancements from digital image processing. Throughout the lunar day, several of the other payloads performed operations that altered the terrain. The Electrodynamic Dust Shield (EDS) [7] payload performed operations to discharge lunar dust from its collection plate, and the Lunar Planetary Vacuum (LPV) instrument collected samples of dust, which caused some clearing of dust from the surface locally around the instrument; this operation also appeared to have cleared the dust from the SFL0 lens. For the SCALPSS team, being aware of the timing of these operations relative to SCALPSS image captures was important to ensure that images taken after significant surface disturbance were not used to build the terrain map informing a plume-induced erosion estimate. Some of these other payload operations, including the Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER) [8] payload surface drilling activities, were captured live by SCALPSS cameras; at a minimum, all other payloads had before/after operation images from

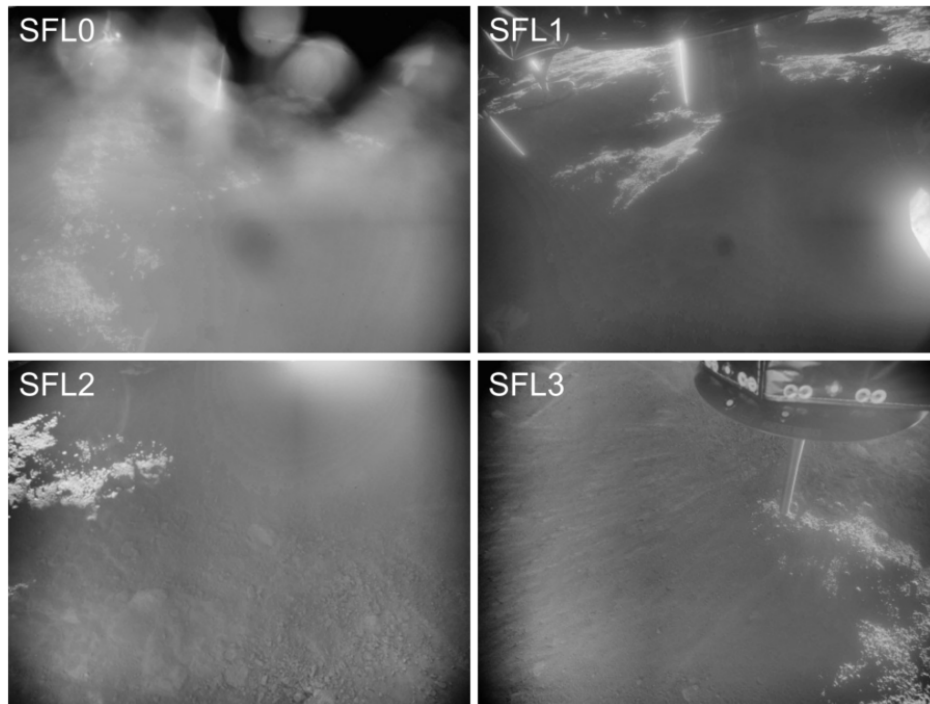


Fig. 2 First post-landing SCALPSS HDR images, taken at 08:35 UTC on March 2, 2025, approximately 10 seconds after touchdown.

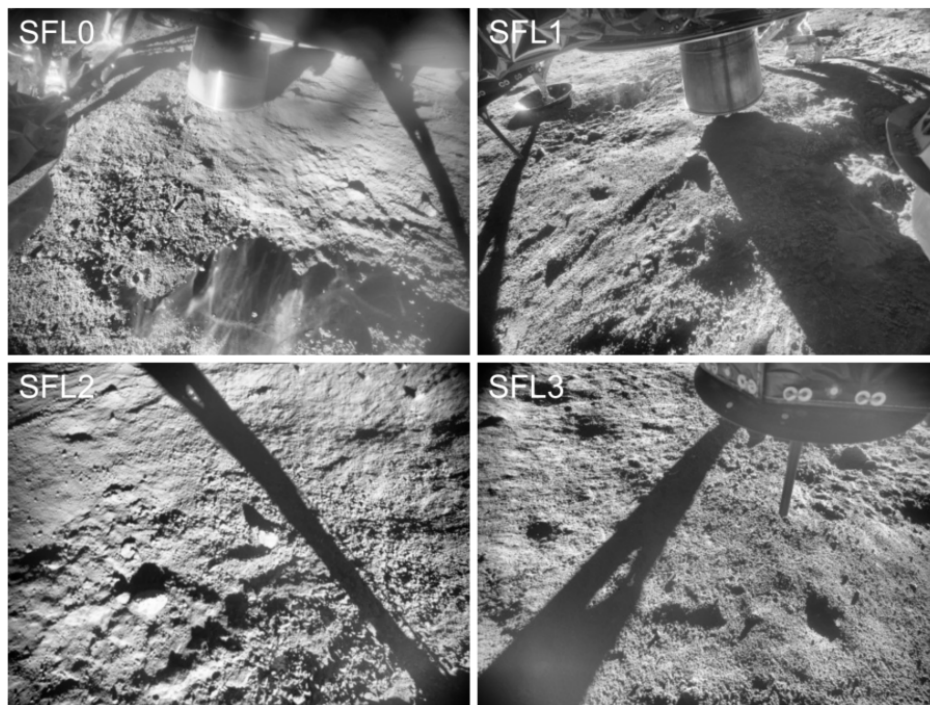


Fig. 3 HDR images from Cap46, taken at 06:46 UTC on March 3, 2025, after other surface operations removed dust from SCALPSS camera lenses.

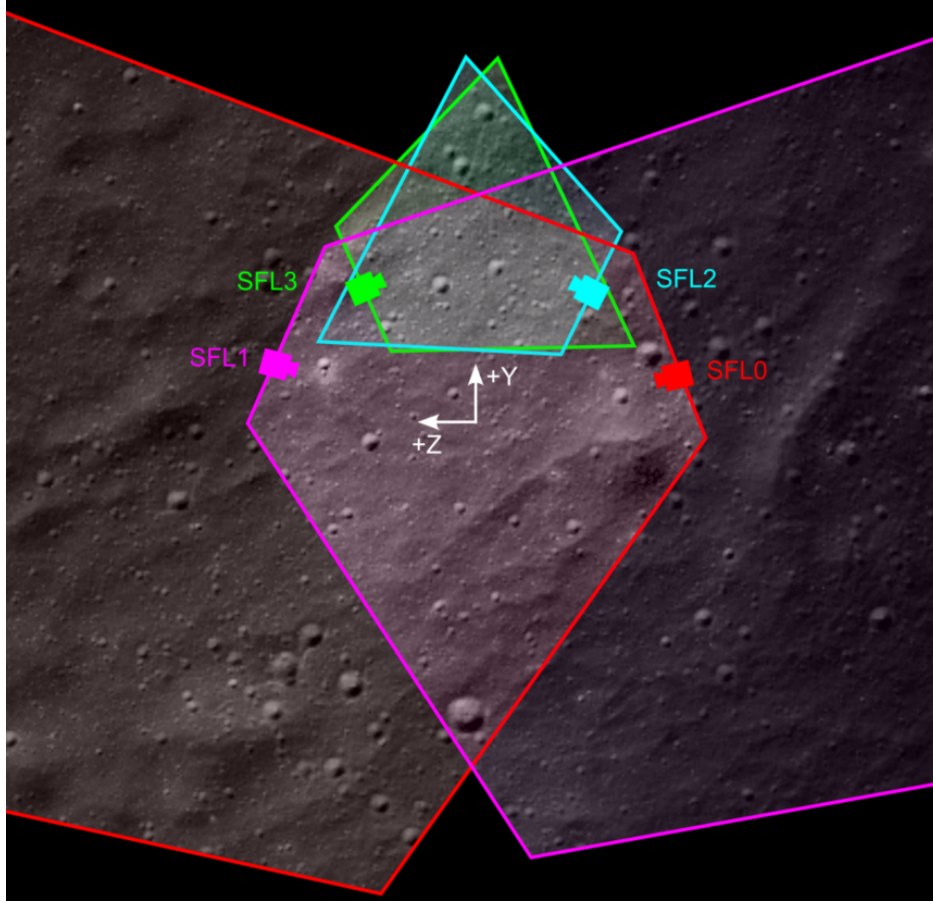


Fig. 4 Computed camera poses over projected simulated views of the four SCALPSS 1.1 SFL cameras, shown as a top-down view.

the hourly SCALPSS captures, so it could be qualitatively (and quantitatively, in some cases) determined whether a payload's operation disturbed the surface. The first image capture taken after the clearing of dust on the SFL0 lens, labeled Cap46, is shown in Fig. 3. By examining the SFL1, SFL2 and SFL3 images from Cap45 in comparison with Cap46, it was determined that minimal surface disturbance occurred in the region around the RCS thrusters, and therefore the much clearer images from Cap46 and onwards could be used to produce a digital elevation map (DEM). Since lunar surface photogrammetry relies on high-contrast features caused by shadows, rocks, craters, and general terrain variation, using many image sets taken throughout the lunar day as shadows swept across the terrain and solar illumination increased greatly improved the resolution of the resulting DEM. The first LISTER pneumatic drilling operation occurred on March 4 at approximately 08:12 UTC. The drill was deployed within view of all four SFL cameras and caused significant disturbance of the surface. As a result, only surface captures taken before this operation (Cap6 to Cap67) have been used to construct the DEMs presented in this paper.

The stereo SFL camera system was calibrated in two phases prior to launch. Each camera was first calibrated intrinsically to remove distortion from the images. After the payload was fully integrated onto the Blue Ghost lander, an exterior orientation (EO) calibration was performed, which provided the orientation and location of each camera within the lander's coordinate frame. For a given pair of stereo images and the known EO, the images can be rectified onto the same 2D plane such that feature detection and matching can be performed. The accompanying paper by Fahringer et al. [9] provides details on the calibration. The final calibrated SCALPSS 1.1 SFL camera system is plotted in a top-down view in Fig. 4, using a camera view simulation software described in [10]. Generic images of the lunar surface, projected from the computed camera poses, are mapped onto the 2D "ground" Z-Y plane. Each simulated camera view superimposed onto the ground plane is highlighted in the same color as the plotted camera icon. The coordinate axes at the center of the plot correspond to the Blue Ghost reference frame, where +Y is aligned to the 'north' direction, and +Z

is aligned with the ‘west’ direction. The $+X$ axis is aligned to the vertical direction (pointing out of the page). The coordinate origin is located approximately at the height of the main engine shield, ≈ 150 mm below the SFL cameras’ mounting height. Cameras SFL0 and SFL1 used 3.37 mm lenses for a wide view ($\approx 93^\circ$ horizontal field-of-view), capturing the ≈ 3 meter diameter area beneath the lander and partial views of all four RCS pair jet impingement regions. Cameras SFL2 and SFL3 were fitted with 5.4 mm lenses ($\approx 67^\circ$ horizontal field-of-view), and aimed towards just one of the four RCS jet pair impingement regions. Since all four cameras were calibrated simultaneously and in the same reference frame, any two cameras can be used as a stereo pair and produce a depth map reconstruction of the surface in the regions where their views overlap. The region on the surface with the most comprehensive stereo coverage is the region on the north-facing side of the lander, particularly beneath the north-facing pair of RCS thrusters. In the SFL images, this region corresponds to the right half of the SFL0 image, the left half of the SFL1 image, and the entirety of the SFL2 and SFL3 images. The SFL0 and SFL1 cameras do have some stereo overlap under the south-facing side of the lander, where shadows from the deployable leg containing the EDS and LPV payloads are visible. However, much of the terrain in the center of the SFL0 and SFL1 views are prevented from being viewed in stereo by the main engine bell, visible in the upper-center of the views from those two cameras.

III. Data Processing Methods

With the cameras calibrated to the Blue Ghost lander’s coordinate frame, feature detection and matching can be carried out to recover depth information. There are several methods available; commercial software was used previously in a similar application by Manginelli et al. [11] to measure plume-induced erosion from the Mars InSight lander. The surface measurements reported in this paper are derived from custom MATLAB codes which leverage a combination of feature correlation methods and are described briefly here. Previous work on measurement accuracy studies for the SCALPSS payload reported in [2] utilized two methods for feature detection: semi-automated cross-correlation and manual point selection. Both methods reported in the previous work required first performing an image rectification on a pair of stereo images, a process wherein the images are warped so that their epipolar lines are horizontal. This results in a single 2D image plane containing both camera images, which are distorted and displayed such that corresponding features are located on the same row of pixels. Within the rectified image plane, a 2D “search” grid of points can be defined in one camera image and a cross-correlation algorithm can be applied to find the corresponding points on the other camera image by simply searching horizontally across the same row of pixels. The cross-correlation approach enables rapid detection of large quantities of matching features on a stereo pair of images, however, it typically works best with images where the cameras have a low convergence angle and the rectified images are not heavily distorted from the raw images. As the convergence angle approaches 90° , the points with the highest cross-correlation coefficient do not necessarily correspond to matching features. In this scenario, manual point selection and matching may be required to match a sufficient number of points across images. The camera configuration for the SCALPSS payload on BGM1 resulted in large convergence angles due to the relatively low height of the aft deck on which the cameras were mounted, and the large separation distance between cameras. For example, a rock and shadow located in the foreground of the SFL0 camera view will be located far from the SFL1 camera, and will appear differently in both the raw images and the rectified image plane, requiring a manually-assisted approach for much of the point-matching for the SFL0-1 stereo pair. When selecting points manually, using the rectified image plane is not required, and points can be selected on the raw images instead, using epipolar lines as guides. A set of $[X, Y]$ image coordinates from a pair of images can then be triangulated to produce a single $[X, Y, Z]$ coordinate in the “world” frame, in this case relative to the Blue Ghost lander’s origin. An example set of manually-selected image points from the SFL2-3 stereo pair, using the Cap46 HDR images, is shown in Fig. 5a, where the SFL2 image points are plotted over the SFL2 image in red (top), and SFL3 image points are plotted over the SFL3 image in blue (bottom). After triangulation of the image points, the resulting $[X, Y, Z]$ coordinates in the lander’s coordinate frame are produced. These are plotted in Fig. 5b, with the top figure displaying the points in the Z - Y plane, with a CAD rendering of the lander underlaid, as if viewing the scene from below the ground plane, looking up. The bottom plot in Fig. 5b contains the same depth data but plotted as a “side” view in the X - Y plane. The computed depth values in this particular dataset range from -460 mm to -540 mm relative to the lander’s origin. By combining multiple datasets, an overall DEM or depth map can be developed.

In addition to point measurements, the shadows cast by features in the terrain and on the lander (landing gear, engine bell, other payloads, etc.) provided high-contrast, easily identifiable line features for matching and triangulation. Multi-point groups of image points based on edges or segments of shadows in the terrain could be correlated between images in a stereo pair by using intensity-based edge-finding algorithms and applying the epipolar line constraint as a

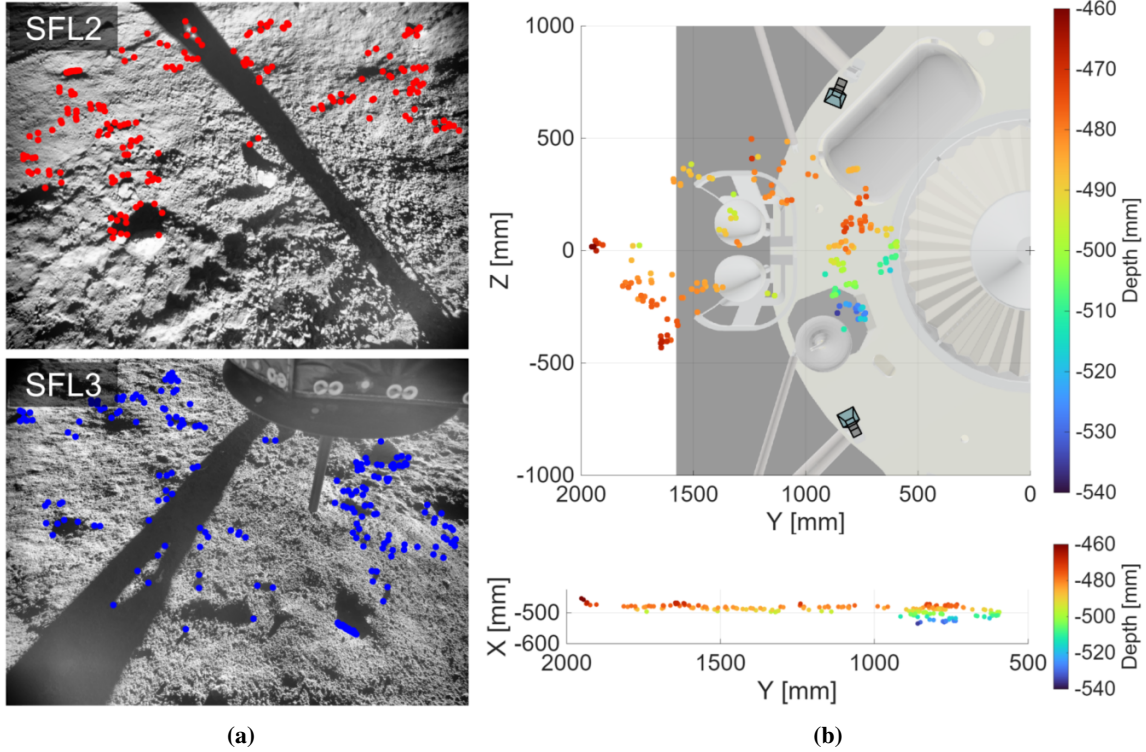


Fig. 5 (a) Manually-selected image points for SFL2 (top) and SFL3 (bottom) for the Cap46 HDR image set. (b) Triangulated depth map values for all image points in the manually-selected SFL2-3 set, plotted in the Blue Ghost Z-Y (top) plane and X-Y (bottom) plane.

guide for the start and end of the profiles. This process greatly reduced the amount of time needed to detect matching points in the images and improved the number of points per image that could be used to build the DEM. Throughout the lunar day, the traversal of these shadows and line features over time as the Sun rose and swept azimuthally across the sky provided more features to improve the resolution of the resulting DEM. An example set of HDR images and shadow-edge-traced image points collected by the SFL1 and SFL3 cameras over a time period of several hours, and the resulting triangulated DEM points, is shown in Fig. 6. The first capture shown in Fig. 6a (Cap35) was taken at 17:46 UTC on March 2, approximately nine hours after touchdown. Much of the terrain is still in shadow since the solar elevation was relatively low ($\approx 8^\circ$) at that time. A thin, straight shadow from the landing gear located to the northeast can be seen in the left edge of the SFL1 image. Segments of that shadow were traced to find the edge; these edge traces are plotted in red on the SFL1 image (top row of Fig. 6a). That same shadow is visible in the top center of the SFL3 camera view, and the segments are plotted in blue on the SFL3 image (bottom row). SFL1 and SFL3 HDR images from Cap48, which took place approximately 13 hours later at 08:46 UTC on March 3, are shown in Fig. 6b; at this time the Sun had risen to an elevation of $\approx 15^\circ$, and more of the terrain was illuminated and the same northeast landing gear shadow had elongated and widened. Another 13 hours later, Cap60 was taken and the landing gear shadows had elongated and moved over the ground. By combining the triangulated depth map points from these three unique image sets taken over the course of roughly one Earth day, a larger segment of terrain can be mapped into 3D space. By incorporating image points from captures taken at finer intervals (e.g., hourly), the spatial resolution of the resulting depth map is improved. As evidenced by the SCALPSS imagery, the lunar surface at the BGM1 landing site is highly textured, and there exists a large range of particle and feature sizes. Therefore, the shadow edges are irregular and can contain gradients in intensity/shading. As a result, the shadow edge tracing method can result in line profiles along the terrain with high variability in depth values. The variability can be attributed to true depth variations from small rocks and clumps in the regolith; it may also be attributable to errors in the edge-finding algorithm arising from differences in camera resolution at the region of interest, intensity smoothing from the image compression, or other factors. Future efforts should be made to assess these effects and improve the overall accuracy of the depth values obtained from the shadow tracing method.

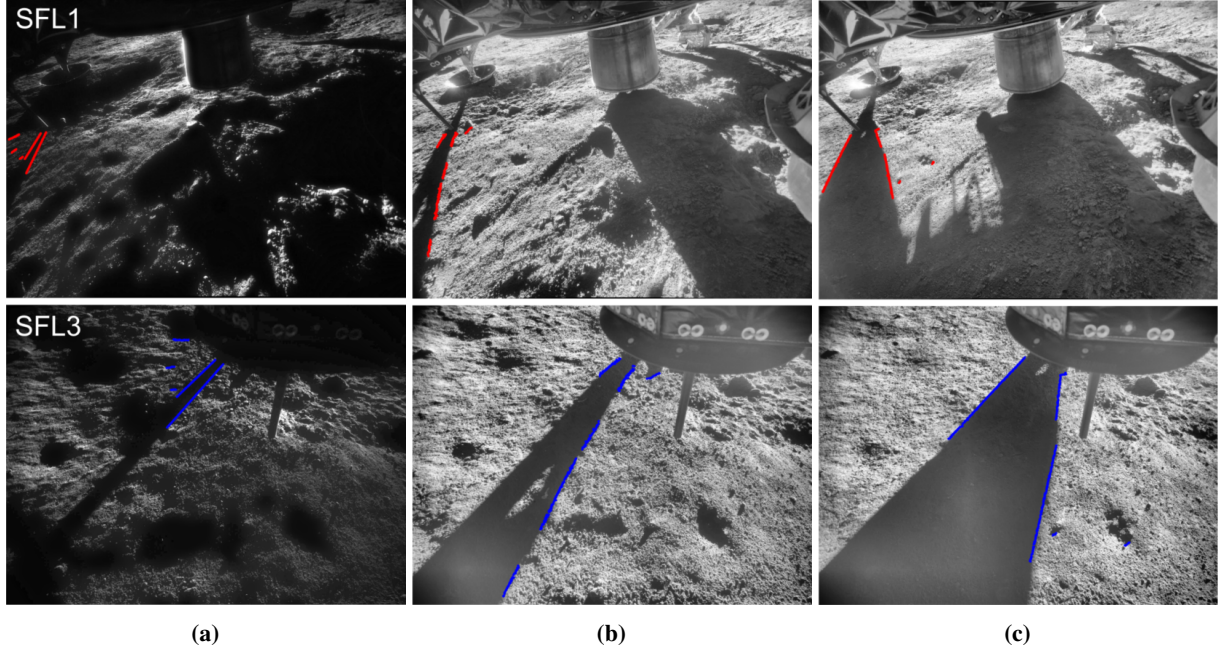
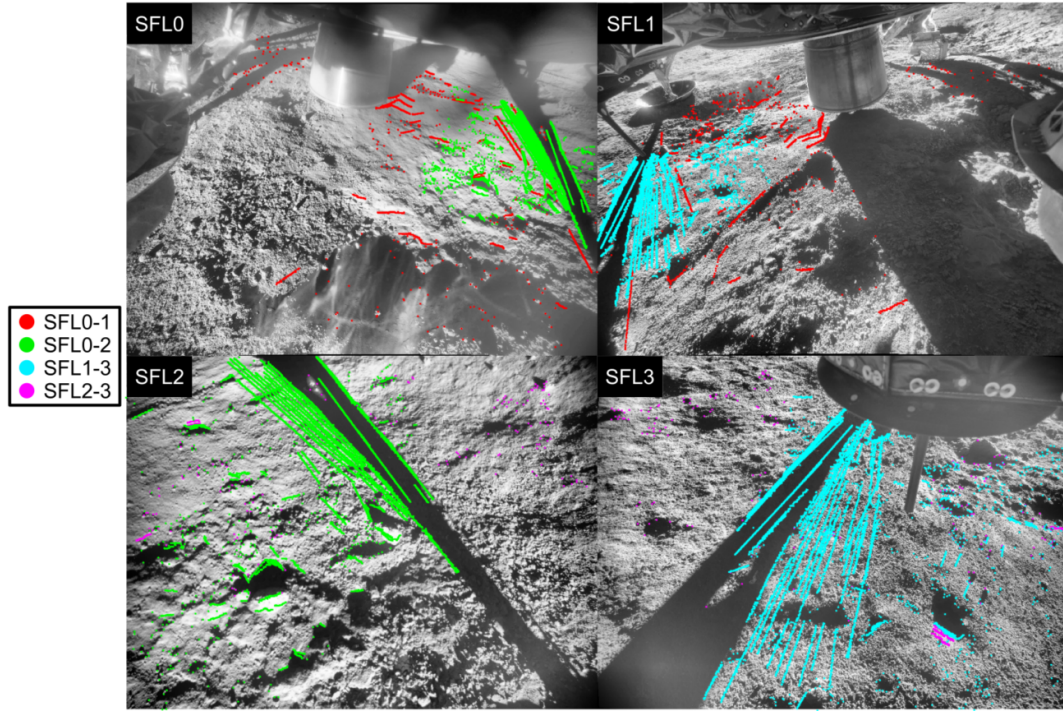
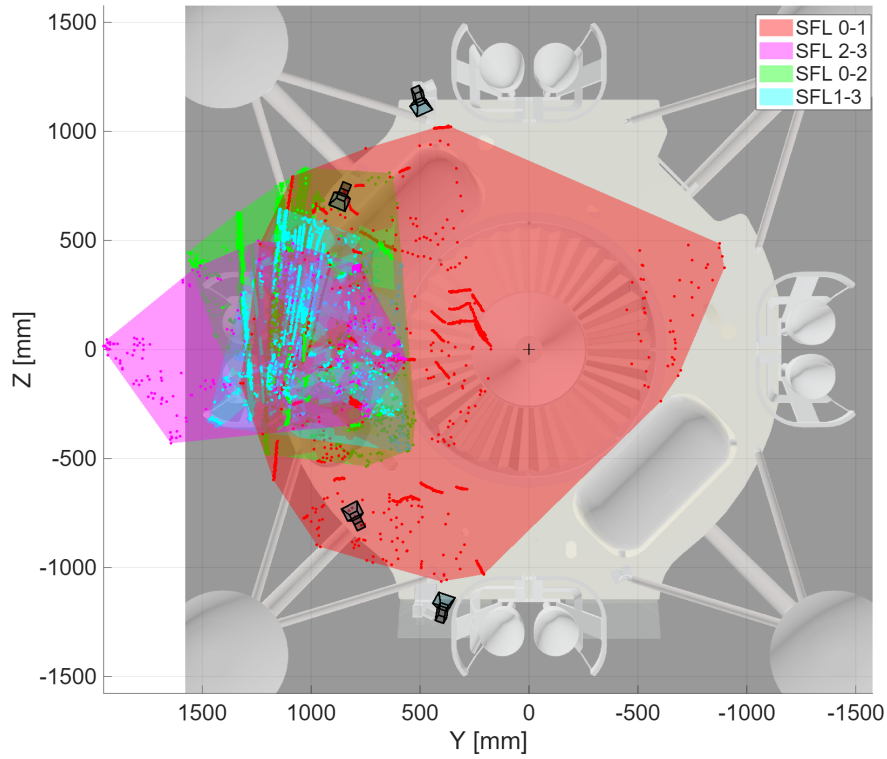


Fig. 6 HDR images with corresponding shadow-edge-traced image points for the SFL1 (top row) and SFL3 (bottom row) stereo pair, taken at three different times: (a) Cap35, taken March 2, 2025 at 17:46 UTC, (b) Cap48, taken March 3, 2025 at 08:46 UTC, and (c) Cap60 taken March 3, 2025 at 21:47 UTC.

As discussed previously, any two SFL cameras can form a stereo pair and produce 3D spatial measurements, since they all have overlapping views and are calibrated to the lander's reference frame. This paper presents measurements obtained by using four of the six possible SFL stereo pair combinations: SFL0-1, SFL2-3, SFL0-2, and SFL1-3. The SFL0-1 camera pair used the same lens focal length (3.37 mm) and had the widest views of the terrain, but from opposite sides of the lander. The SFL2-3 pair, also equipped with the same (5.4 mm) lenses, had improved resolution of a smaller region on the ground, the region beneath the north-facing pair of RCS thrusters. For the SFL0-2 and SFL1-3 camera pairs, the cameras within each pair were located closer together and pointed in similar directions; this generally improves the effectiveness of a cross-correlation-based approach for point matching and reduces distortion in the rectified image plane, but the low camera separation distance has been shown to have a negative affect on accuracy. These two factors can have competing effects, as discussed in previous work [2]. The SFL1-2 and SFL0-3 stereo pairs are not considered in the current paper due to their redundancy to the other pair options, but should be included in future efforts towards more complete terrain reconstructions. After combining and triangulating all of the image points for each stereo pair, four separate DEMs, all in the Blue Ghost's reference frame, were produced. The image points are plotted over each of the four SFL camera views from Cap46 in Fig. 7a, though multiple captures between Cap29 and Cap60 were used to collect the image points. The points are plotted by stereo pair, with the red points being matched from the SFL0-1 pair, magenta from SFL2-3, green from SFL0-2, and cyan from SFL1-3. Triangulating each set of image points results in a point cloud of $[X, Y, Z]$ coordinates in the lander's reference frame. Each of the point clouds is then converted to a surface mesh using Delaunay triangulation [12], such that all the triangulated points are contained within the bounds of the mesh. The four meshes are plotted in translucent colors on the same axes in Fig. 7b, with their contained image points also included and the Blue Ghost CAD rendering underlaid. As expected, the SFL0-1 stereo pair surface plot covers the largest area beneath the lander, though the points are more sparsely distributed towards the centerline of the vehicle. The SFL2-3, SFL0-2, and SFL1-3 surface plots all cover a similar area beneath the north pair of RCS thrusters (located along the vehicle's $+Y$ axis) since the narrower fields-of-view of SFL2 and SFL3 are the limiting factor. The overlapping SFL2-3 views extend farther in the $+Y$ direction than the other stereo pairs, providing points outside the expected footprint of the north RCS jet impingement regions. The depth map computed from each of these individual and combined stereo pairs is presented and discussed in the following section.



(a)



(b)

Fig. 7 (a) Cumulative compiled image points for all four SFL cameras using image captures from Cap29 to Cap60, comprising both manually and semi-automatically selected/correlated points, colored by stereo pair. (b) Surface plots of point clouds, plotted in the Z-Y plane underneath the Blue Ghost CAD rendering, colored by stereo pair.

IV. Post-Landing Terrain Estimate

The four point clouds resulting from the four stereo pairs were combined to produce an overall point cloud containing approximately 25,000 points. Of these points, approximately 3,000 were selected manually and 22,000 were selected using the shadow tracing methods described previously. The combined image points, which were shown in Fig. 7a in Sec. III, are plotted over the Cap46 HDR SFL images again here in Fig. 8, with the depth values obtained during triangulation added on the color axis. As stated previously, the lander's $+X$ axis points in the upwards direction, so smaller (more negative) values indicate that the measured points are farther from the lander (deeper in the surface). The depth map presented in this paper is a preliminary terrain measurement, and further work is required to assess the relative accuracy and agreement between the different stereo pair combinations. Factors such as camera separation, cross-correlation efficacy, image distortion in the rectified image plane, and robustness of each pair's stereo calibration should all be considered. In addition to accuracy assessments, it should be noted that the DEM presented in the current work was generated from a relatively sparse dataset, especially for the regions outside the north pair of RCS thrusters, due in part to limited stereo overlap outside of that region. Planned efforts to improve the resolution of the DEM, such as using more image pairs with manually-selected points, will be reported in future work. Furthermore, commercial photogrammetry data processing methods, such as those reported in [11], should also be applied to the images to assess relative accuracies of the different methods.

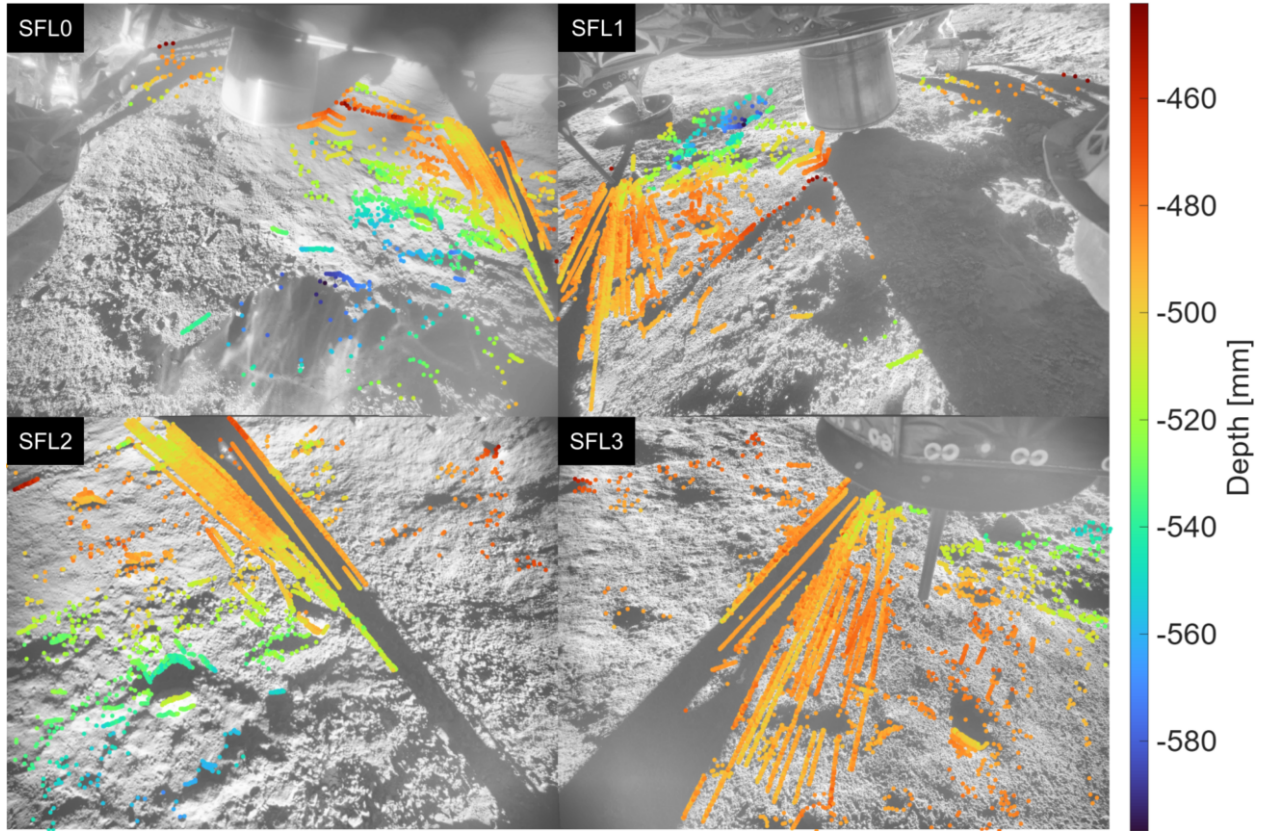


Fig. 8 Image points plotted over the Cap46 HDR captures for each SFL camera, color coded by depth relative to the lander's coordinate system origin, for the combined post-landing depth map.

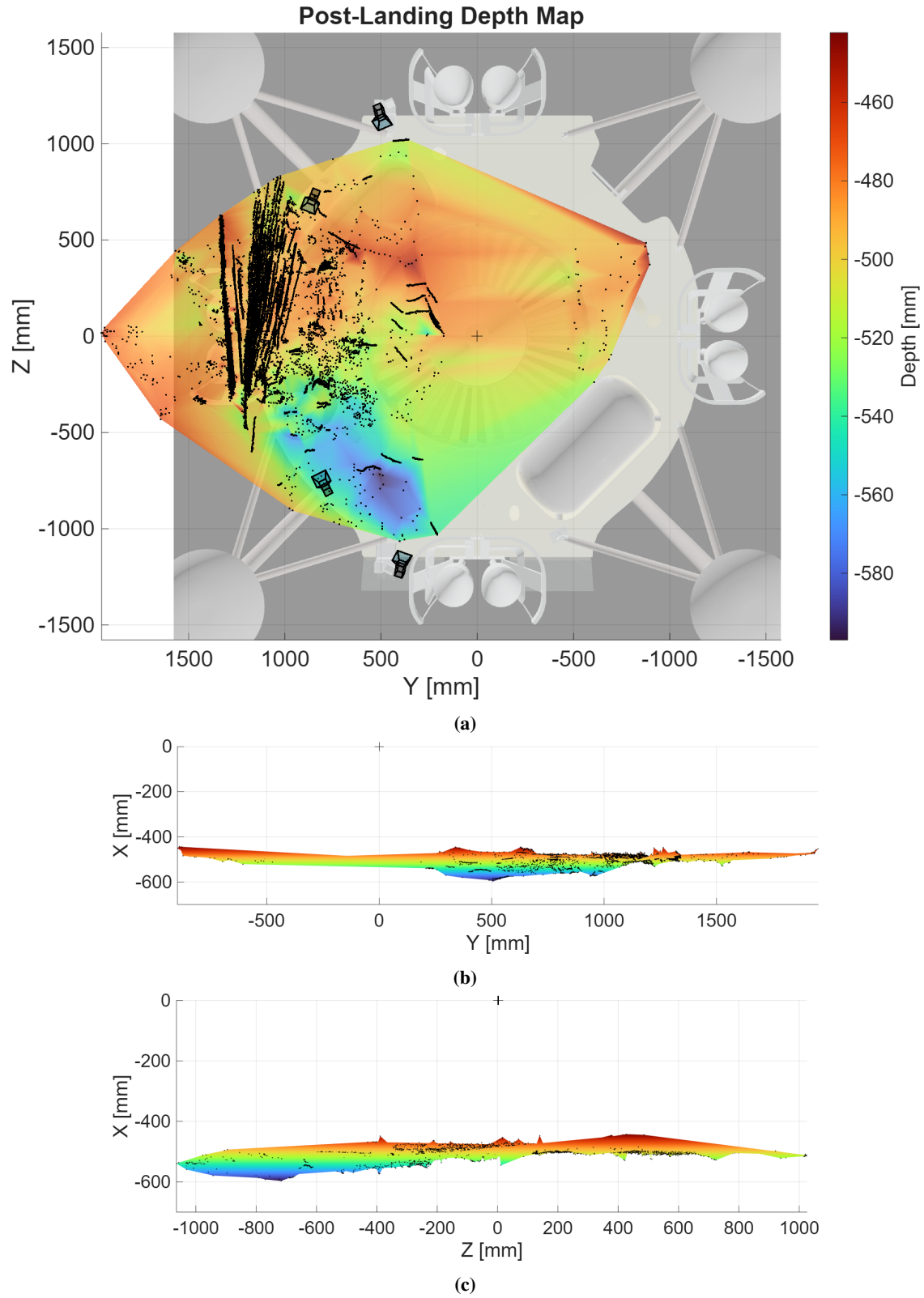


Fig. 9 (a) Combined post-landing depth map, colored by depth value and plotted on the Y-Z plane with the Blue Ghost CAD underlaid. (b) Side view of depth map in the Y-X plane. (c) Side view of the depth map in the Z-X plane.

In general, the depth values of the dataset presented here vary from -442 mm to -597 mm, a range of roughly 150 millimeters (≈ 6 inches). The terrain covered by the landing gear shadows sweeping across the regolith in the first two days of the surface mission is evidenced by the many straight lines appearing on the right and left sides of the SFL0 and SFL1 images, respectively, and in the middle portions of the SFL2 and SFL3 images. The depth values of these shadow-traced lines tend to fall in the middle of the full DEM depth range, typically in the -480 mm to -500 mm range, excluding some outliers caused by rocks protruding from the surface. Some larger rocks are responsible for the higher range of depth values seen in this DEM, for example the elongated ridge-like feature seen in the top right section of the SFL0 image, plotted in dark red. There is a deeper region of terrain located in the front of the SFL0 camera view and back of the SFL1 camera view; this is evidenced qualitatively by the dark shadowed region containing caustic reflection patterns from the lander’s multi-layer insulation (MLI). The depth values in this deepest region, measured primarily by the SFL0-1 camera pair, appear to be roughly 60 – 80 mm deeper than the surrounding terrain measurements. The region where this deeper terrain is located does not correspond to an area immediately under a pair of RCS thrusters, as might be expected if a vertical landing and touchdown is assumed to have occurred. This is illustrated more clearly by the surface plot overlaid with the Blue Ghost CAD rendering, shown in Fig. 9a, where the DEM and CAD rendering are plotted as if viewing them from beneath the lander, looking upwards. Figures 9b and 9c show side views of the plotted DEM in the Y - X and Z - X planes, respectively, to further contextualize the relative depth of the measured terrain. The deeper region, appearing dark blue in the surface plot, is located roughly between the north and east pairs of thrusters. Further analyses of pre-landing terrain from the imagery reported in the accompanying papers by Danehy et al. [13] and Weisberger et al. [14], along with the lander’s trajectory reconstruction, are needed to contextualize the post-landing terrain depth map presented in this paper and deduce whether it was plume-induced. Further refinement of the post-landing DEM by using additional feature detection and tracking methods and/or commercial software should also be performed.

V. Conclusions and Ongoing Work

This paper presents an overview of the methods and results for the first post-landing terrain estimate of the Firefly Aerospace Blue Ghost Mission 1. The region of the lunar surface measured within the stereo overlap of the SCALPSS SFL cameras was focused primarily beneath the north-facing pair of RCS thrusters; however, some points outside of this region were seen by both the SFL0 and SFL1 cameras and were also measured. Four different stereo pair camera combinations across multiple HDR image captures from throughout the first ≈ 37 hours after touchdown were used to build the preliminary DEM presented here. The terrain measured by all four cameras concentrated beneath the north pair of thrusters is relatively flat, with most terrain features falling within ≈ 20 mm millimeters in measured depth of one another. One localized area of deeper terrain is on average ≈ 60 – 80 mm deeper than the other measured terrain; this is further evidenced by the visible shadowing of that region throughout the first two days of the surface mission. Further efforts are needed to assess whether the observed post-landing terrain features were a result of plume-surface interaction from the landing and to provide a definitive plume-induced erosion estimate, which can be used for correlation to computational and predictive modeling methods. These efforts will need to synthesize multiple data products as they become available, including but not limited to: (a) the reconstructed as-flown descent trajectory, (b) the pre-landing terrain and flowfield measurements from both SCALPSS SFL and LFL cameras, (c) coupling of results with computational models, and (d) refinements of the post-landing terrain measurement (as were discussed in Sec. III).

The stereo image processing methods applied in the current paper and planned for continued development can also be applied to other aspects of the mission to extract 3D spatial measurements. Of primary importance to the plume-surface interaction problem (in addition to erosion) is the development and evolution of a so-called “ejecta sheet,” which is a phenomenon that has been observed in previous lunar landings [15], and which was also observed during BGM1, as reported by Danehy et al. [13]. The number, position, and ejection angle of the ejecta streaks as a function of time during the descent can be quantitatively estimated by applying the same feature tracking principles that were used in the current paper. Furthermore, individual particles seen by multiple cameras during the descent such as those reported by Weisberger et al. in [14] can also be tracked in stereo. For image captures that occurred later in the surface mission, stereo measurements can be repeatedly made to assess the effect of other NASA payload operations on the lunar surface over time.

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